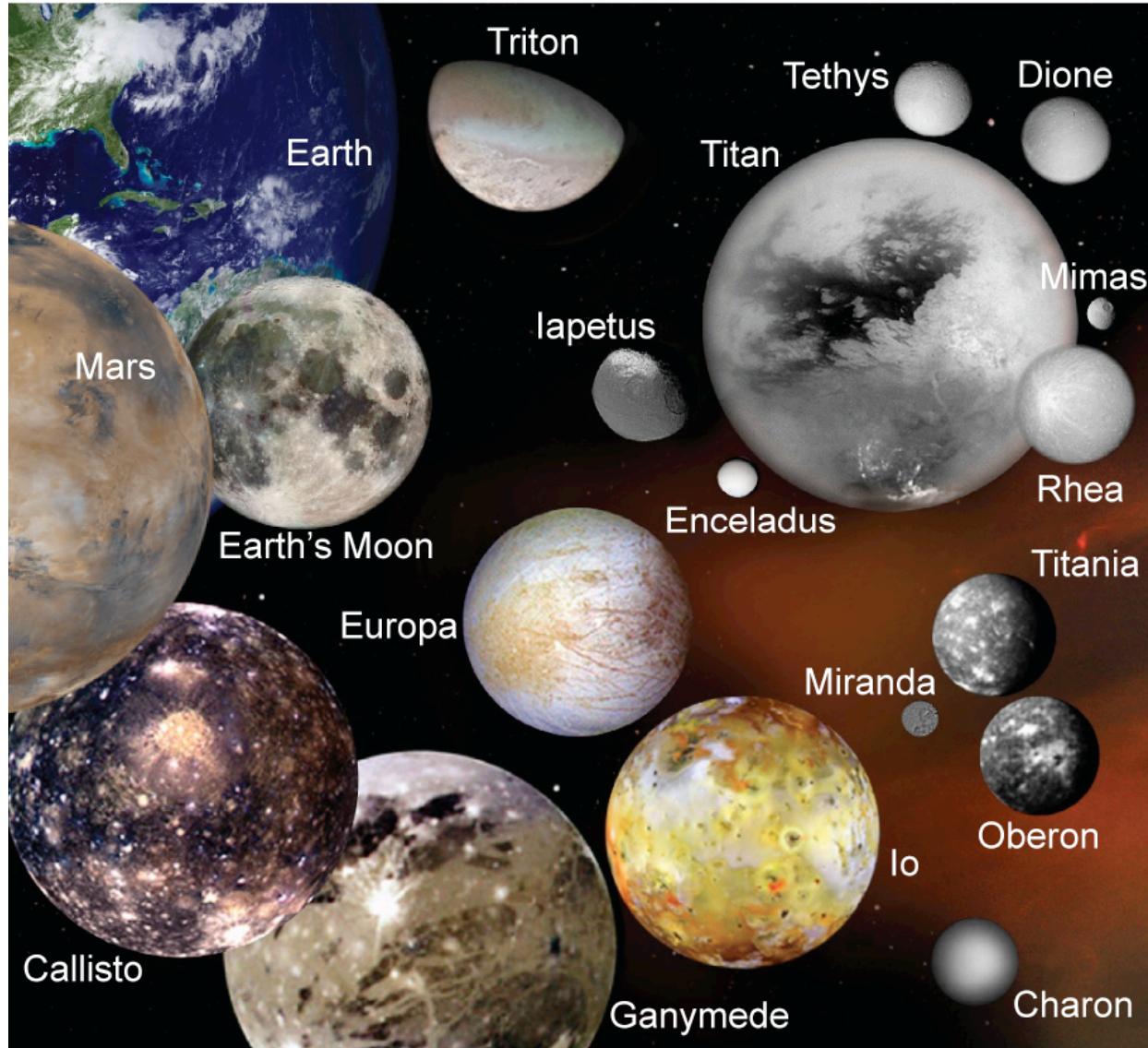




Différenciation des objets de taille moyenne





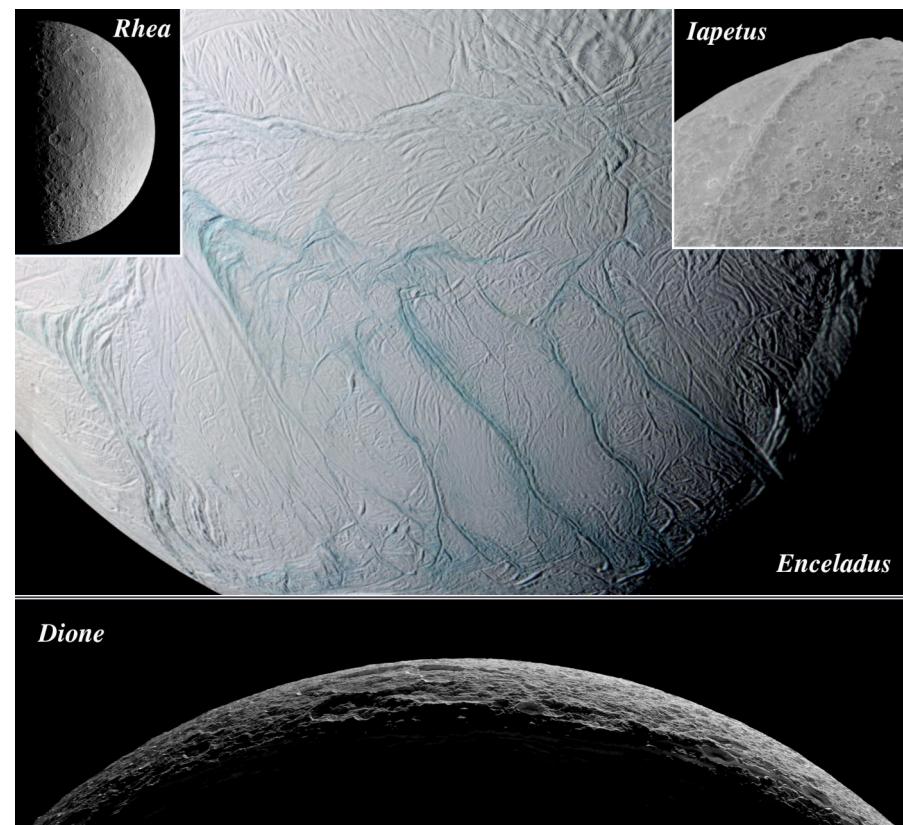
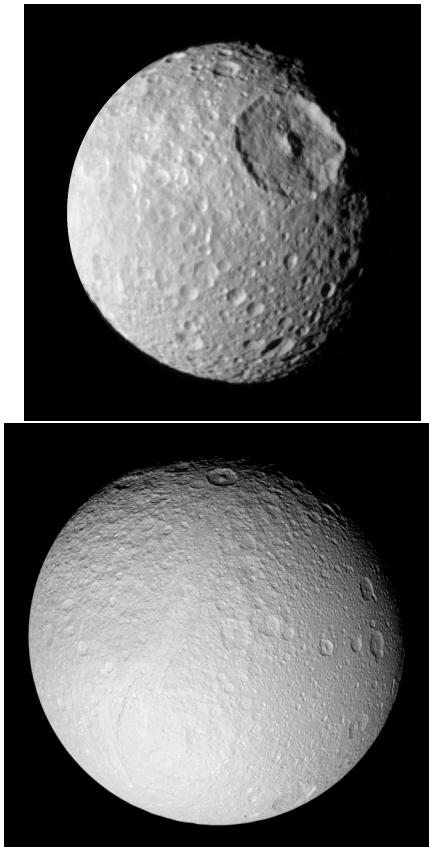
Plan de la présentation

- **Données**
 - surface (imagerie, rayon, spectroscopie)
 - Intérieur (champ de gravité →masse, degré de différentiation; champ magnétique (degré de différentiation))
- **Objets**
 - Cérès ([Dawn](#))
 - Les petits satellites de Saturne ([Cassini](#)) – [Japet](#), Encelade et les autres
 - Europe ([Galileo](#) – [EJSM](#))
 - Callisto - Titan – Ganymède ([Galileo](#) – [Cassini/Huygens](#) – [EJSM](#))
 - Pluton-Charon et KBOs ([New Horizons](#))
- **Modèles**
 - Densité (composition chimique, porosité)
 - Evolution thermique (conduction – convection [timing])
 - Séparation glace/silicates



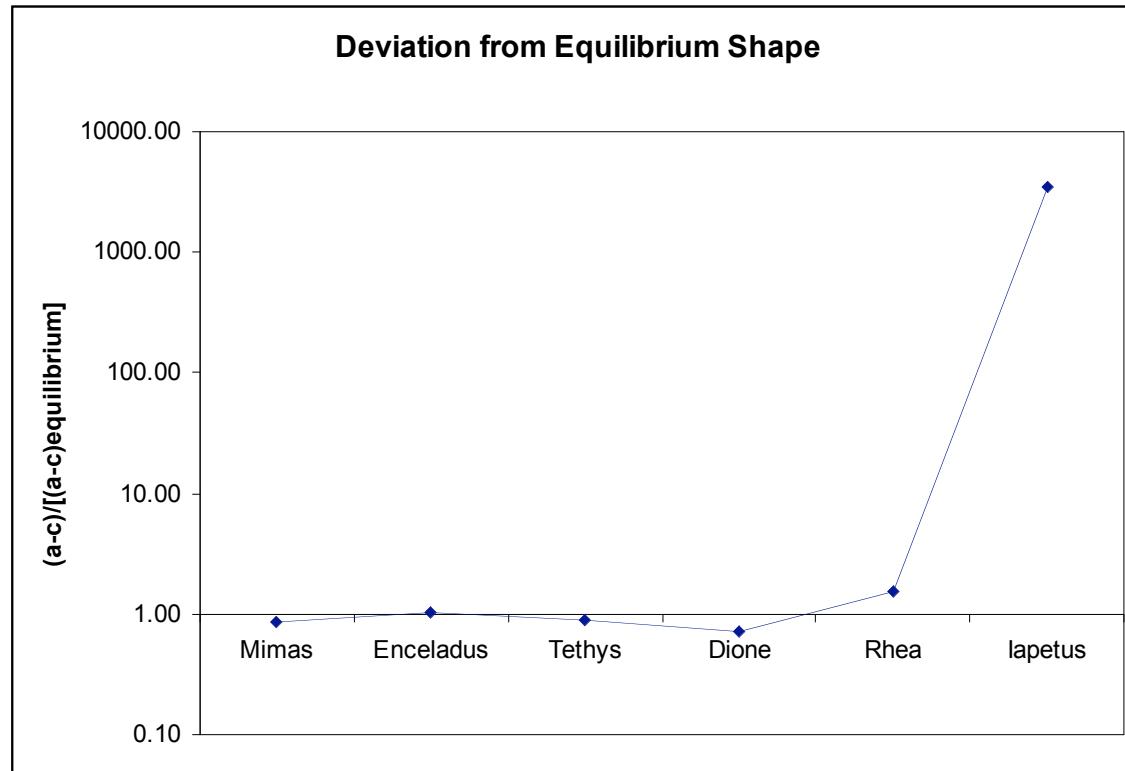
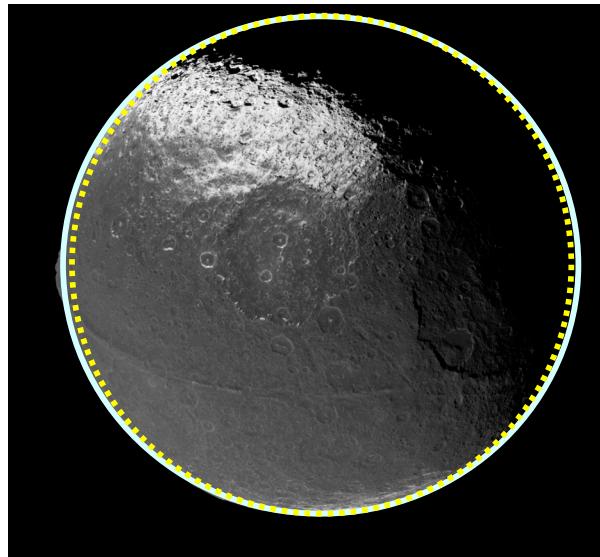
Les satellites de Saturne

	Mimas	Enceladus	Tethys	Dione	Rhea	Iapetus
Density (kg/m3)	1153,6	1607,1	955,5	1469	1233,2	1087,8
Radius (km)	198,8	252,31	536,3	562,5	764	734,5





Forme des satellites de Saturne

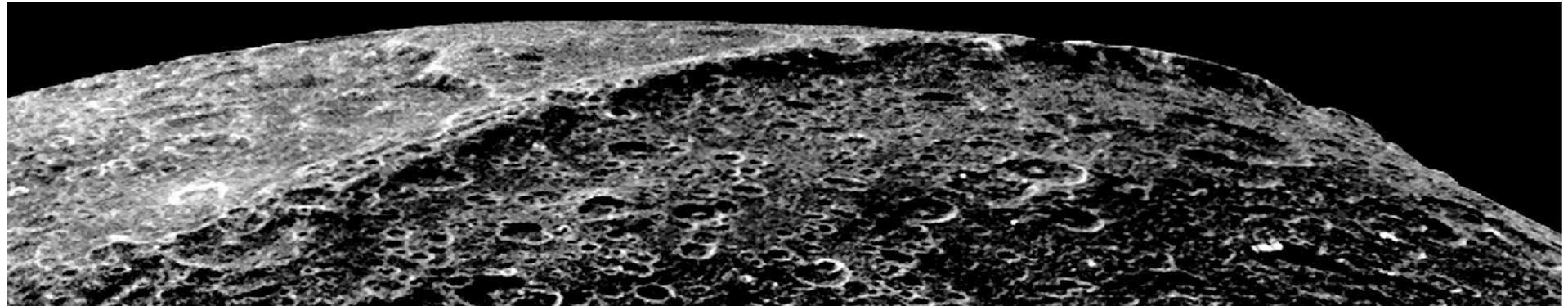


Shapes of the Saturnian icy satellites (Thomas et al., LPSC 2006)

L'aplatissement de Japet correspond à une rotation de 16h
Son excentricité est de 2.43%



Montagne équatoriale



La ‘ride’ équatoriale de Japet fait 18 km de haut et s’étend sur au moins 1600 km au niveau de l’équateur. Elle est très cratérisée. Comment expliquer cette ride?

- Pli équatorial
- Accrétion de matière au niveau de l’équateur
- L’autre solution

La surface de Japet est constituée de glace avec des zones riches en CO₂

Les deux observations ([ride équatoriale](#) et [forme correspondant à une rotation de 16h](#)) peuvent-elles s’expliquer par un seul modèle?



Evolution thermique et orbitale

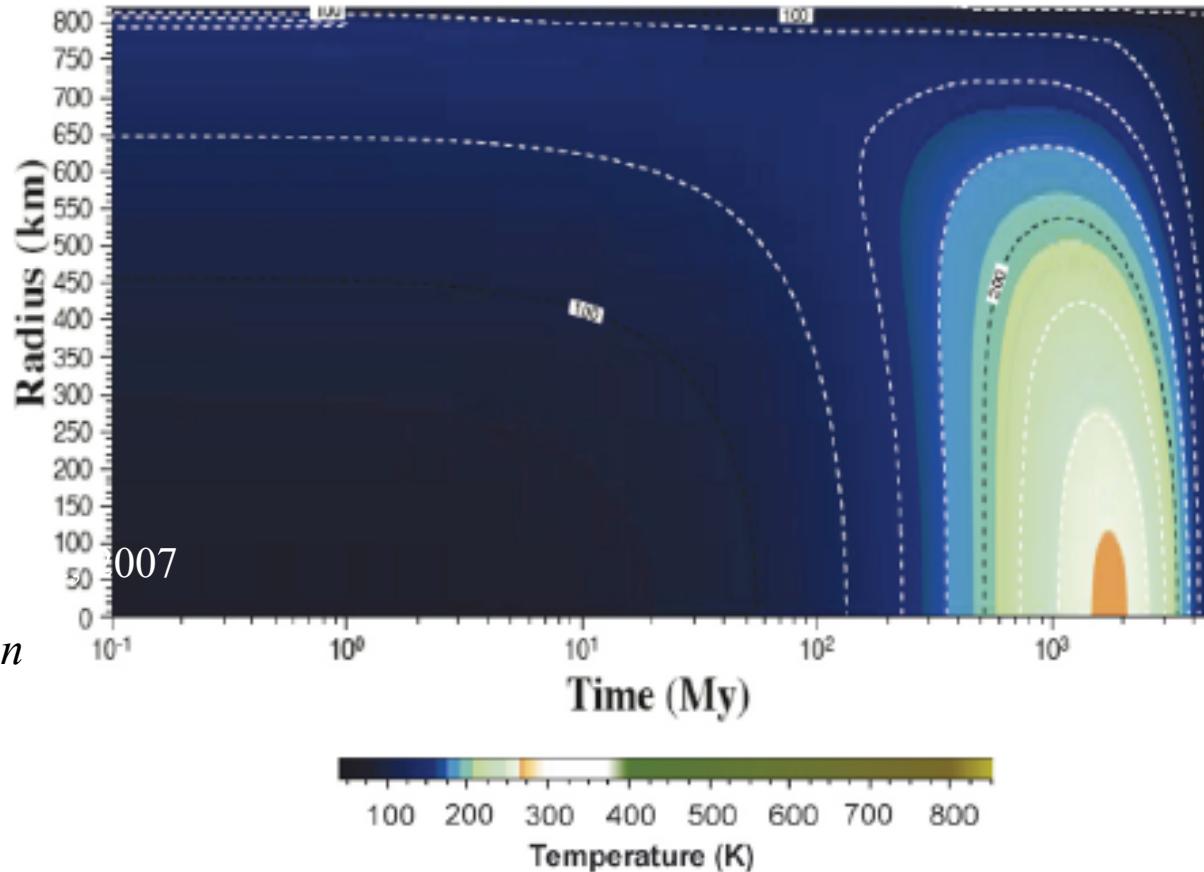
$$\frac{d\omega}{dt} = -\frac{3k_2 GM_p^2 a^5}{CD^6 Q}$$

Le facteur de dissipation
Q vaut: $Q = -k_2 / \text{Im}(k_2)$

$$e(t) = e_0 \exp(\tau \cdot t)$$

$$\tau = \frac{57}{8} \frac{M_{Japet}}{M_{Saturn}} \left(\frac{R_{Saturn}}{a} \right)^5 \frac{k_{Saturn}}{Q_{Saturn}} n$$

$$-\frac{21}{2} \frac{M_{Saturn}}{M_{Japet}} \left(\frac{R_{Japet}}{a} \right)^5 \frac{k_{Japet}}{Q_{Japet}} n$$



Evolution thermique classique 1D sphérique: LLRI, porosité, paramètres dépendent de T,
accretion produit une augmentation de température de 40 K

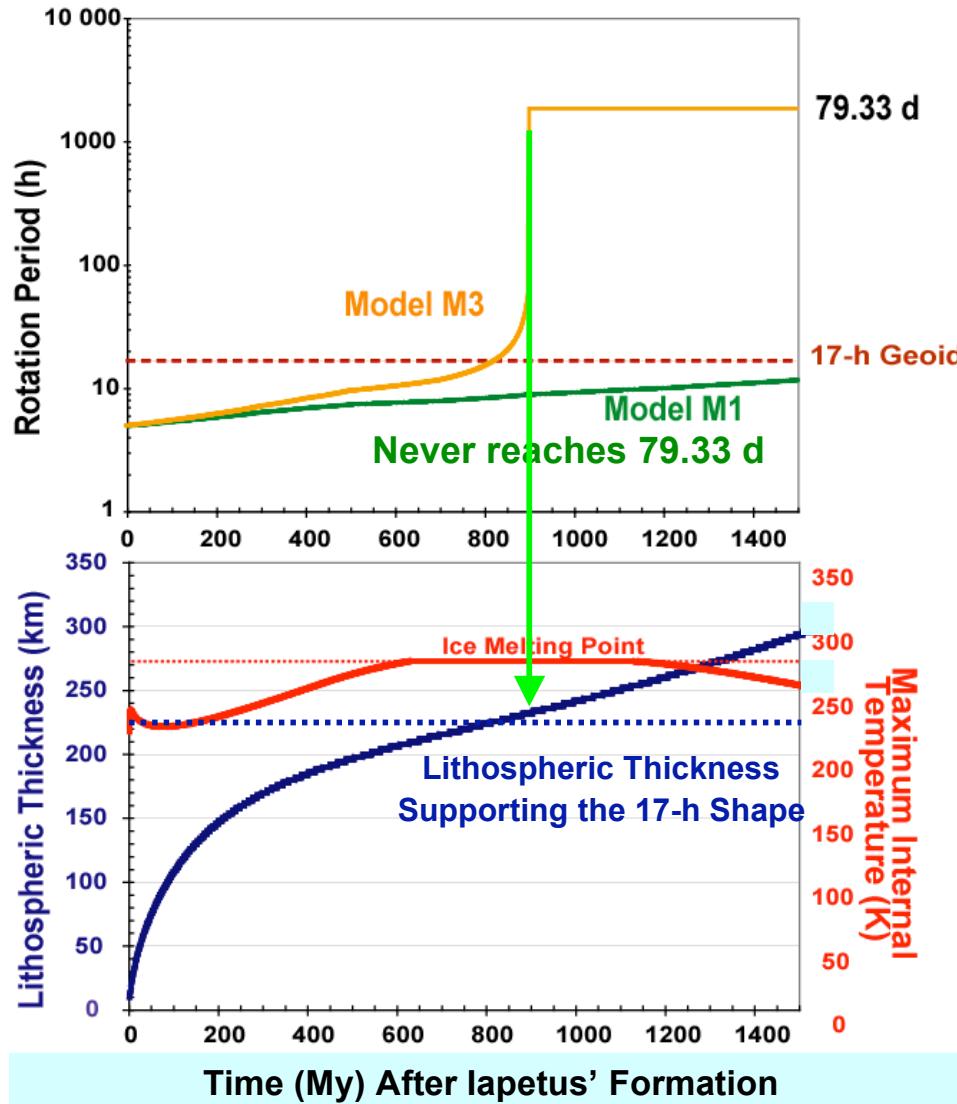


Evolution thermique et orbitale

$T_{accret} = 4 \text{ My}$
after CAIs

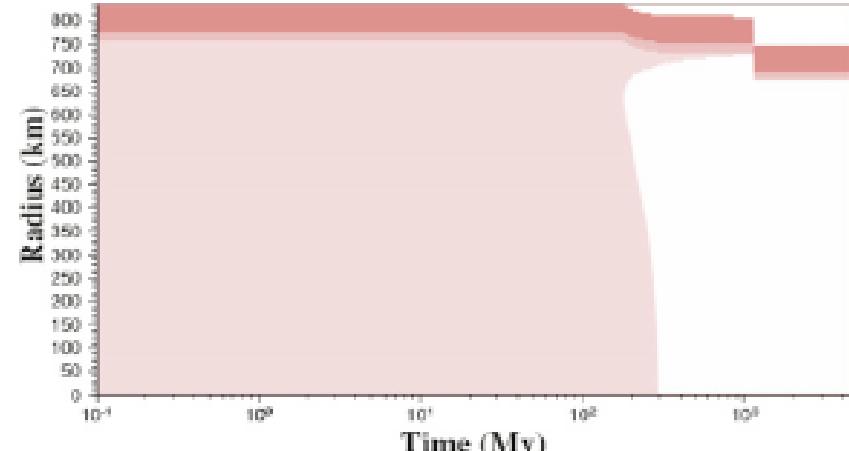
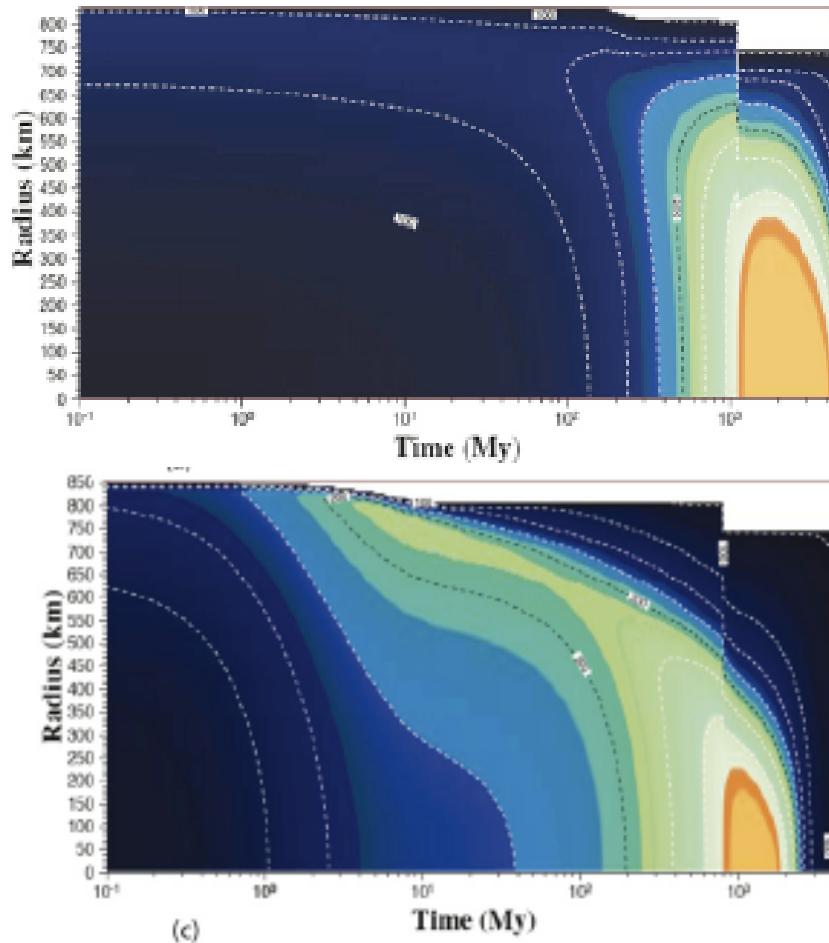
$h = 0.7$

$T_0 = 5 \text{ h}$





Evolution thermique et orbitale

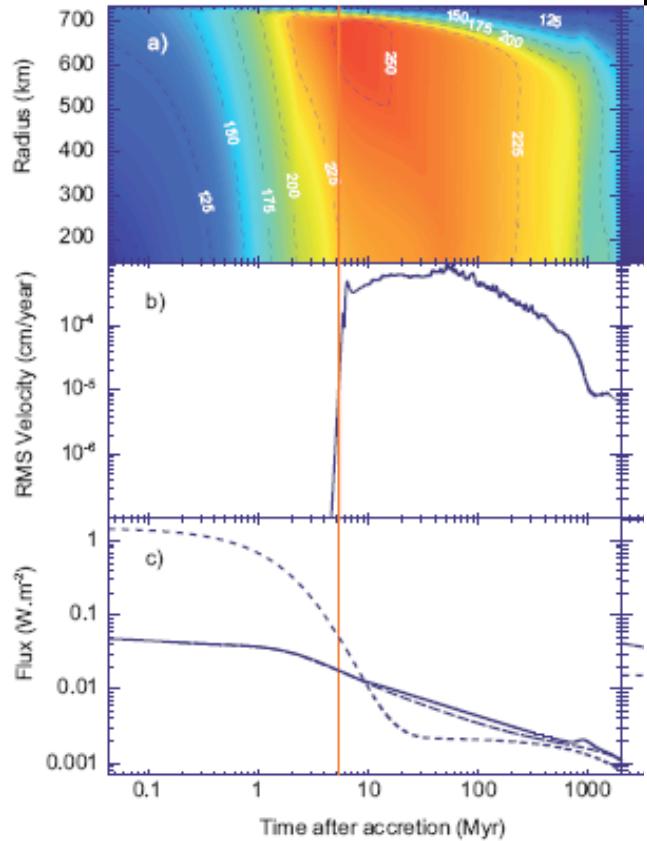


Evolution thermique avec porosité

Evolution thermique avec porosité et
SLRI (^{26}Al)

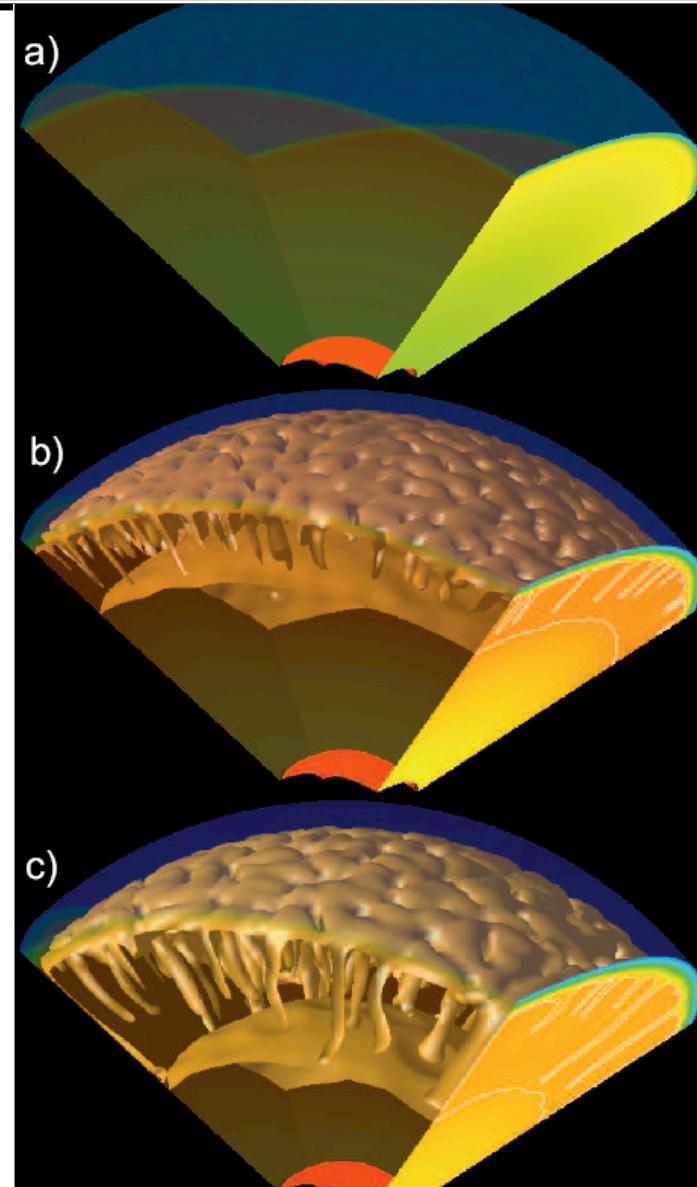


Convection in mid-sized icy moons



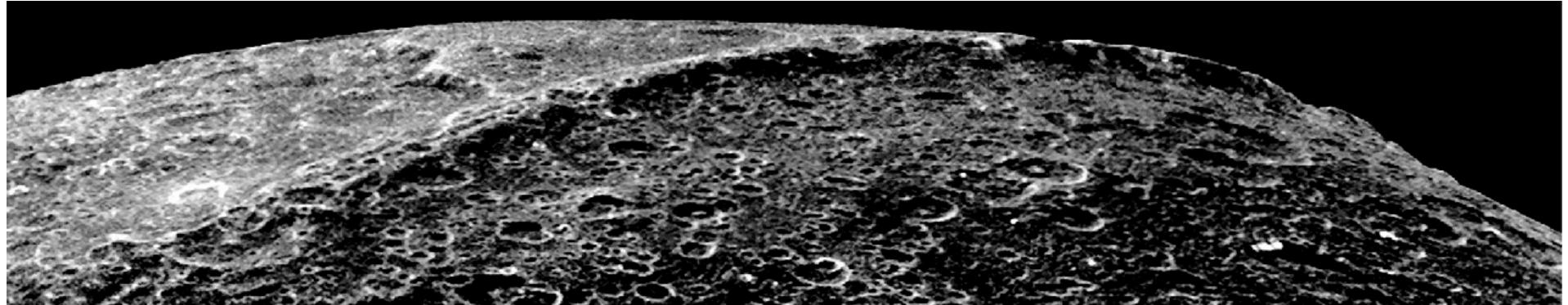
Convection in Iapetus (Robuchon et al., 2008)

- Convection starts before viscosity is low enough for despinning to occur (Iapetus)
- Necessary to have a transient viscosity (Burgers rheology)





Conclusion pour Japet



Lors du changement rapide de rotation, la forme a change et a produit une diminution de surface pour un même volume → pourrait expliquer la montagne équatoriale

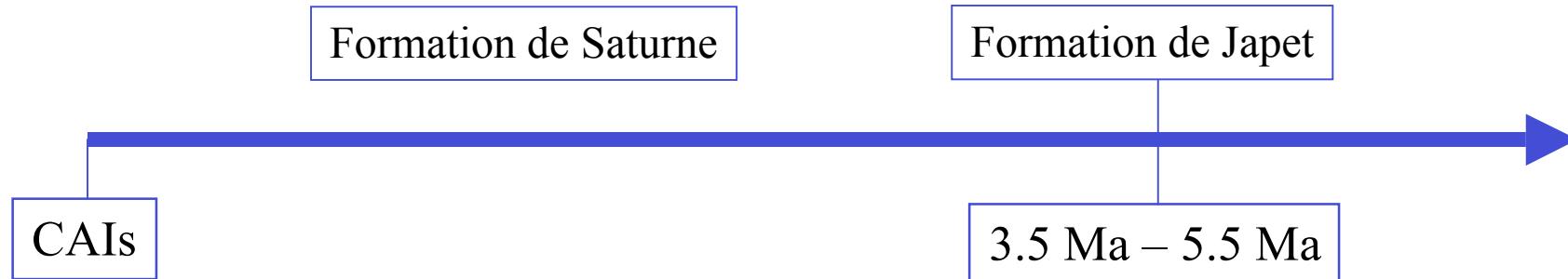
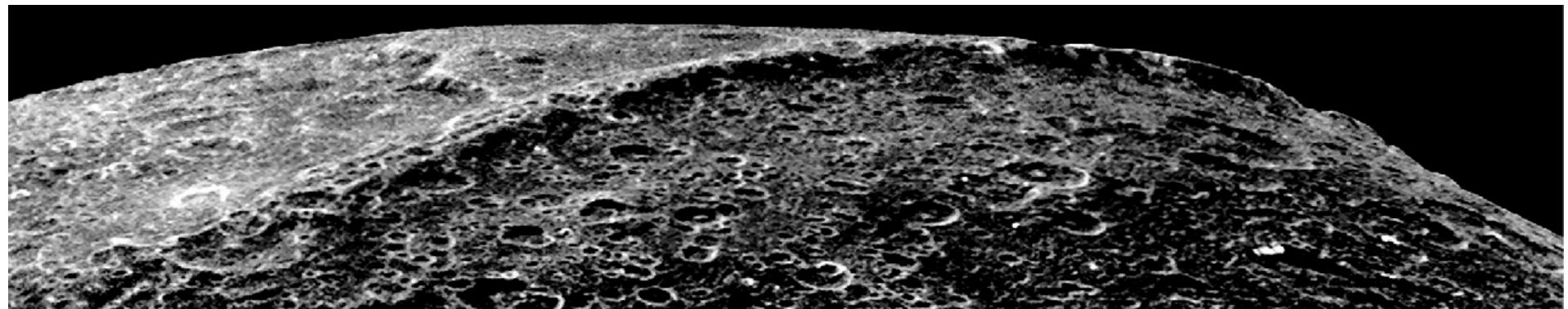
Dans la gamme de paramètres possibles, il existe un jeu de paramètres qui permet d'expliquer la forme d'équilibre à 16 h (cœur suffisamment chaud pour permettre la dissipation **ET** lithosphère suffisamment épaisse pour conserver la forme).

La convection thermique semble se mettre en place avant que la viscosité soit suffisamment faible pour permettre le passage à une rotation synchrone. Nécessité d'un modèle un peu plus complexe (mais plus réaliste) de viscosité.

Sur la base de la quantité de chauffage nécessaire au départ, il faudrait que Japet soit formé entre **3.4 et 5.4 Ma / CAIs**.



Conclusion pour Japet





Plan de la présentation

- **Données**
 - surface (imagerie, rayon, spectroscopie)
 - Intérieur (champ de gravité →masse, degré de différentiation; champ magnétique (degré de différentiation))
- **Objets**
 - Cérès ([Dawn](#))
 - Les petits satellites de Saturne ([Cassini](#)) – Japet, Encelade et les autres
 - Europe ([Galileo](#) – [EJSM](#))
 - Callisto - Titan – Ganymède ([Galileo](#) – [Cassini/Huygens](#) – [EJSM](#))
 - Pluton-Charon et KBOs ([New Horizons](#))
- **Modèles**
 - Densité (composition chimique, porosité)
 - Evolution thermique (conduction – convection [timing])
 - Séparation glace/silicates



Encelade

Rayon : 252.31

Masse: $1.08 \cdot 10^{20}$ kg

Masse volumique: 1607.1

Fraction de silicates: 0.57

1348.87

P_{rad} : 0.37 GW

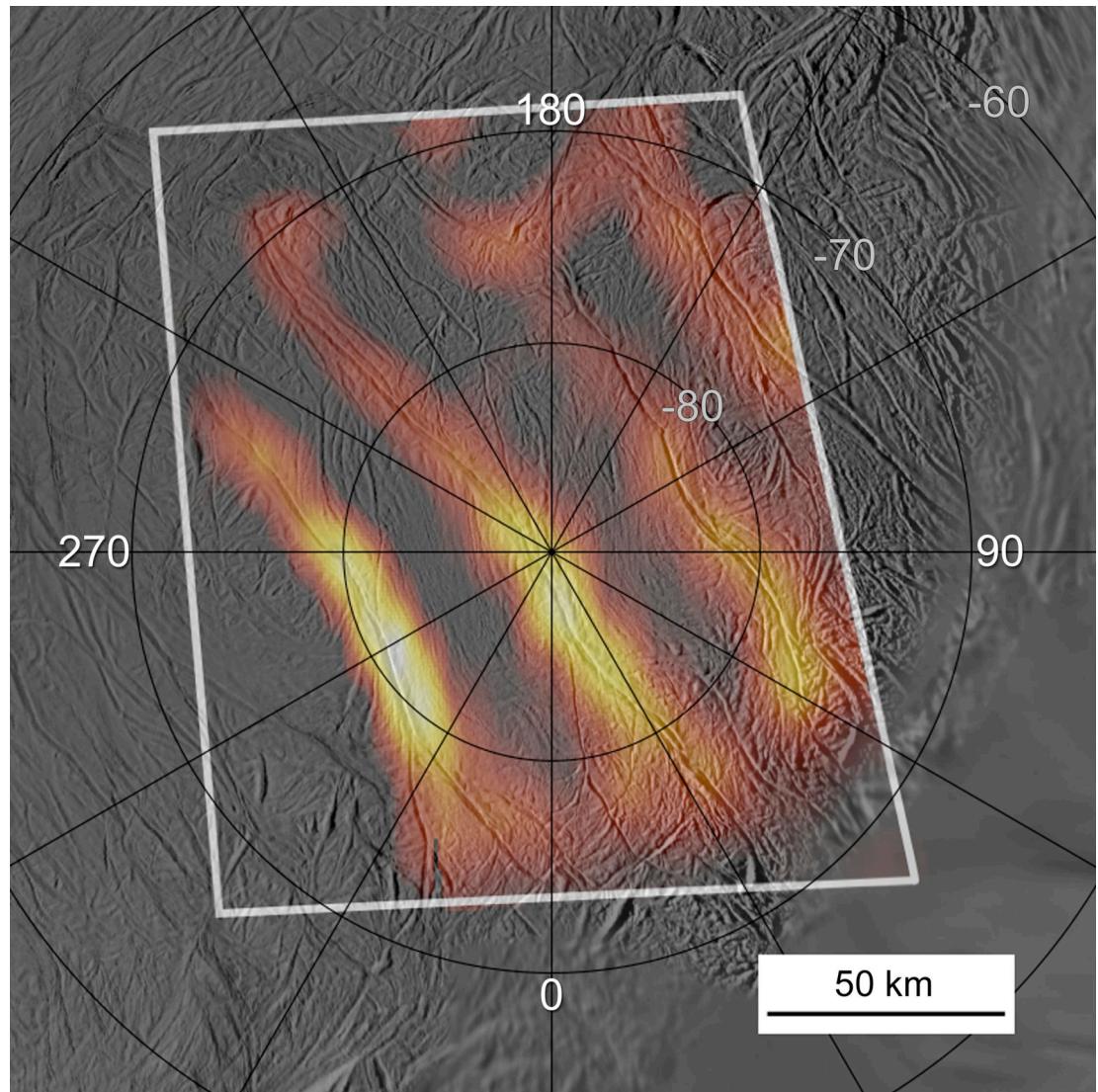
P_{PoleSud} : 3-7 GW

$g = 0.113 \text{ m/s}^2$

Rotation: 32.885 h

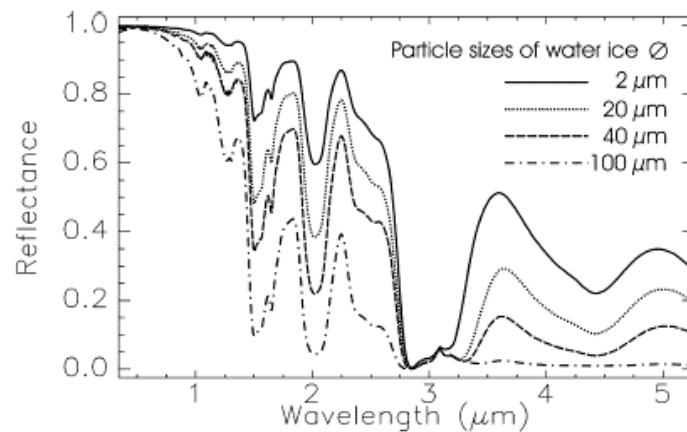
Excentricité: 0.0045

- Friction le long des failles (Nimmo et al, 2007)
- Energie de marée dissipée à l'intérieur du satellite (Tobie et al., 2008)





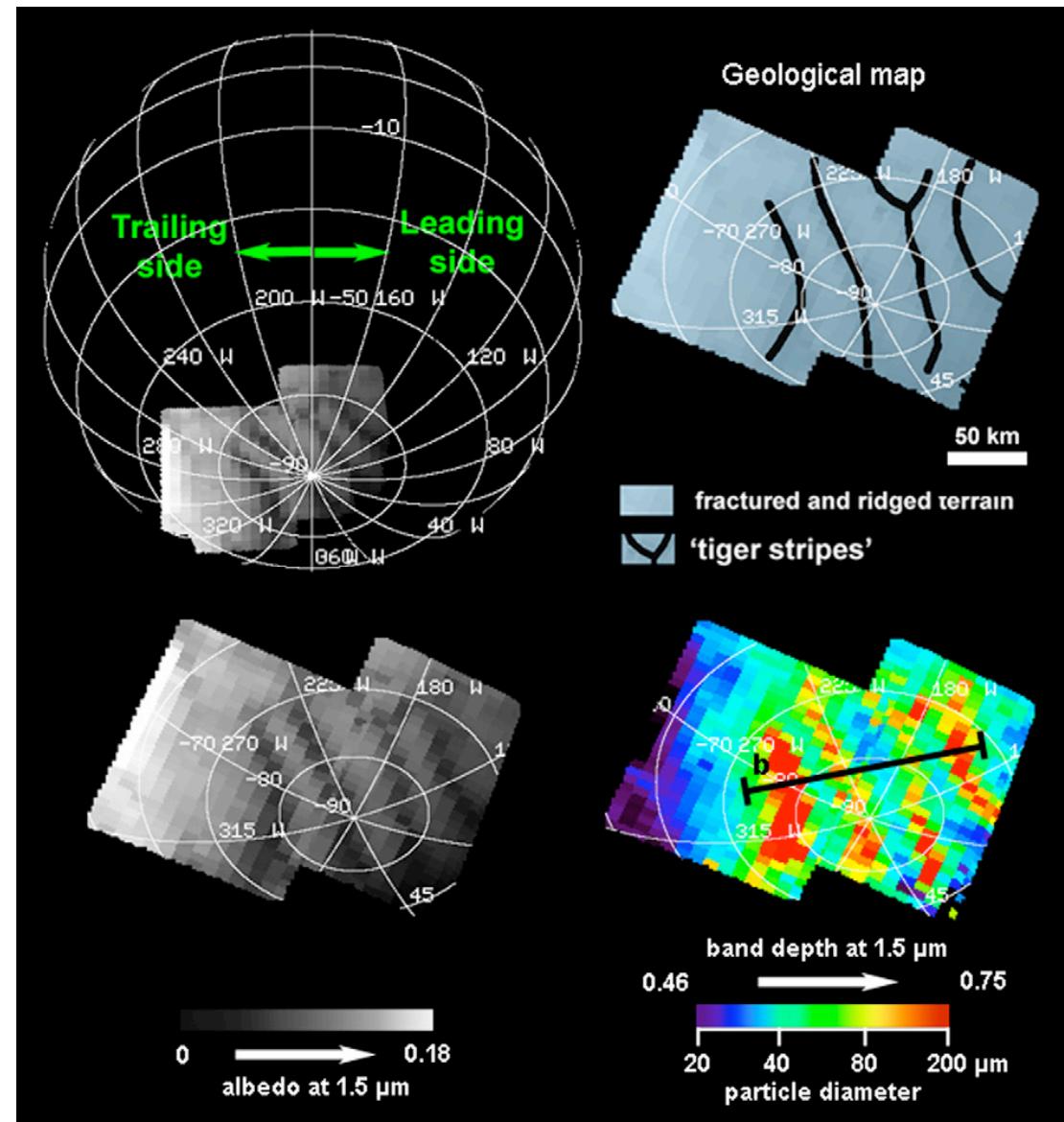
Encelade: observations



Instrument VIMS: Encelade est couvert de glace d'H₂O et la taille des grain est plus grande au niveau des failles

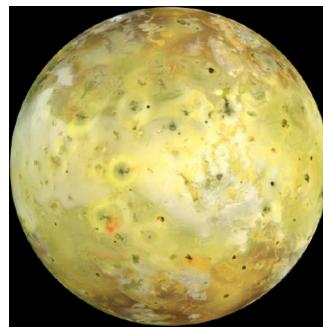
Instrument INMS: ⁴⁰Ar est éjecté avec un flux de $5 \cdot 10^{-5}$ kg/s.

→ Observations plus compatibles avec une origine interne.





Chauffage interne de quelques objets



6371 km	1822 km	2575 km	252.3 km
$6 \cdot 10^{24}$ kg	$0.0894 \cdot 10^{24}$ kg	$0.1345 \cdot 10^{24}$ kg	$0.000108 \cdot 10^{24}$ kg
5525 kg/m^3	3528 kg/m^3	1881 kg/m^3	1608 kg/m^3
2/3 Silicates and 1/3 iron	Silicates	Ice and silicates	Ice and silicates
42 TW	80 TW (2 W/m^2)	Model: 750 GW	6 GW in the South Pole area

Radiogenic power is proportional to mass – cooling – tidal heating



Encelade: chauffage de marée

$$\frac{\partial D}{\partial t} - \frac{\partial}{\partial t} \left[\mu (\nabla u + \nabla^\tau u) \right] = -\frac{\mu}{\eta} D$$

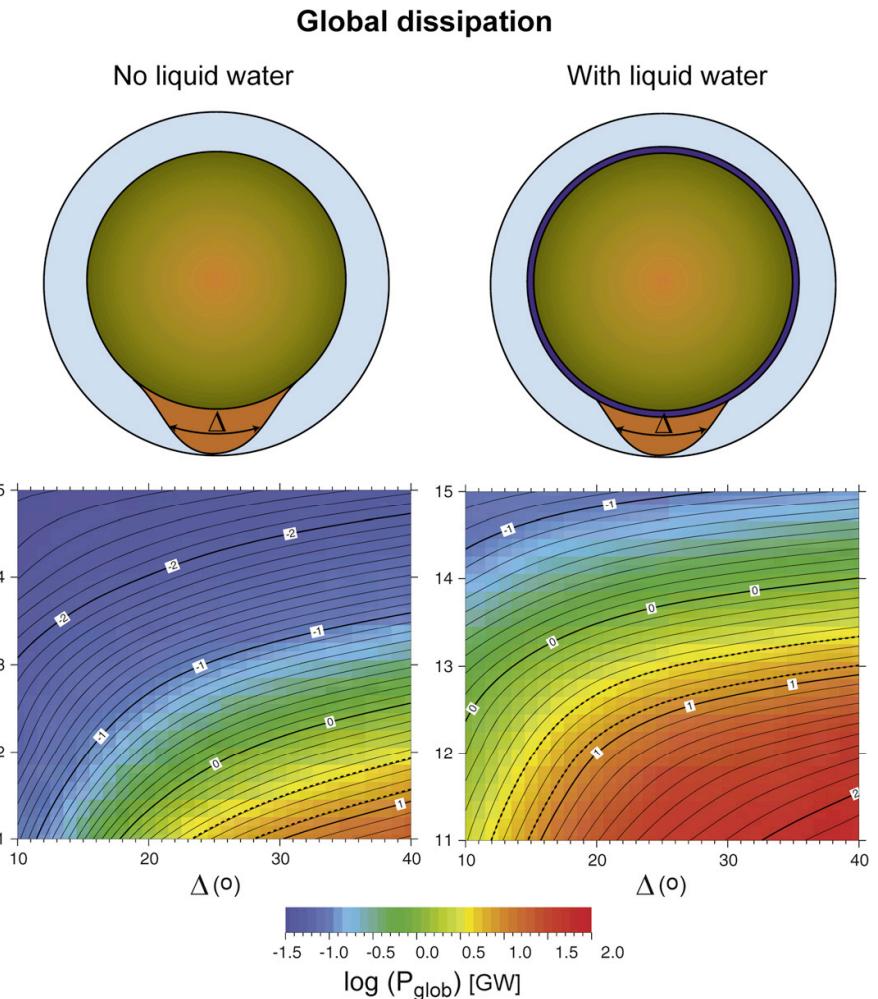
$$\nabla \cdot (-pI + D) + f = 0$$

$$\Phi(r, \theta, \phi) = \omega^2 r^2 e \left[-\frac{3}{2} P_2^0(\cos \theta) \cos(wt) + \frac{1}{4} P_2^2(\cos \theta) \{ \cos(wt) \cos 2\phi + 4 \sin(wt) \sin 2\phi \} \right]$$

$$h(r, \theta, \phi) = \frac{1}{T} \int_t^{t+T} \frac{D : D}{2\eta} dt$$

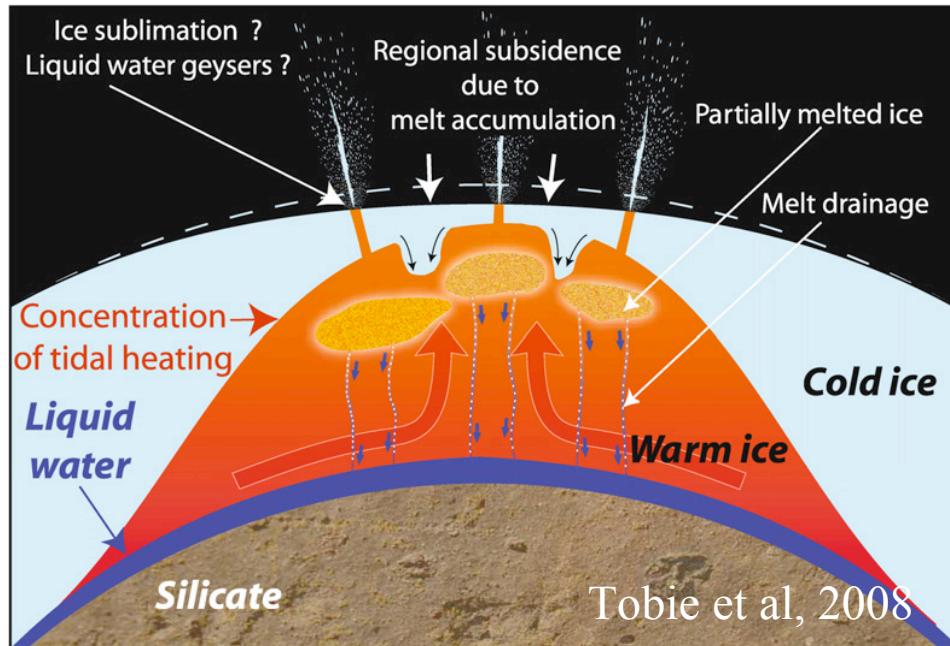
$$\eta = \eta(Temp)$$

$$P_{glob} = \int_V h dV$$





Encelade: conclusions



- tidal heating in a low viscous region → internal melting of the ice shell.
- Melt percolation and accumulation at the base of the ice shell could explain the apparent subsidence.
- Melt percolation replenishes the liquid layer.

Convergence of warm materials heated over a relatively broad dissipative region toward the narrower tectonic active region at the SouthPole is expected. The release of internal heat to the surface would occur along localized tectonic features (“tiger stripes”) during episodic resurfacing events associated with lithospheric expansion and small-scale convection. Upwellings of warm ice below the ridges would finally promote sublimation of near-surface ice and destabilization of clathrate reservoir, or possibly melting of water ice, resulting in the formation of jets as observed by Cassini (Kieffer et al., 2006; Porco et al., 2006)..

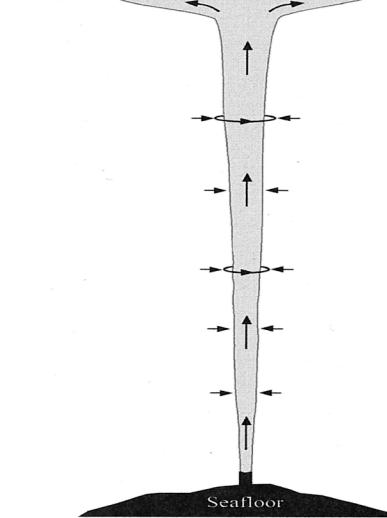
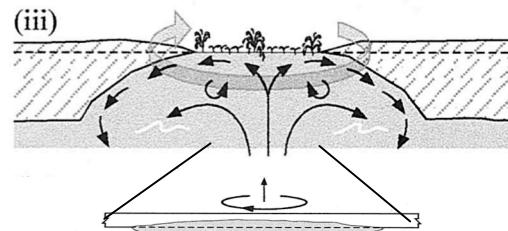
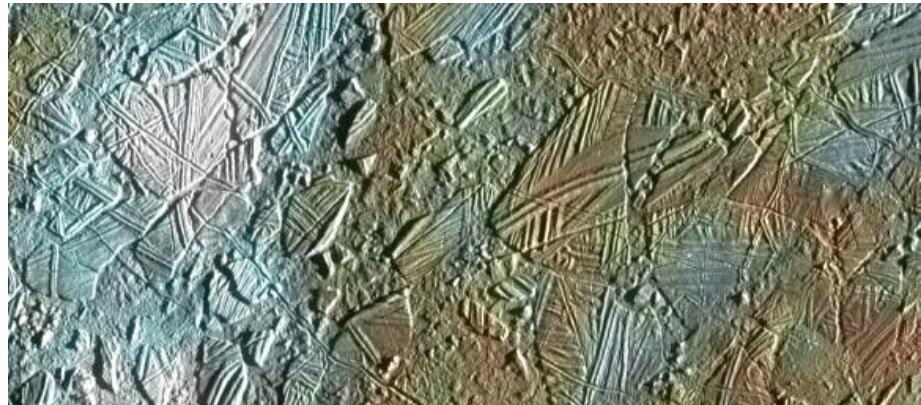


Plan de la présentation

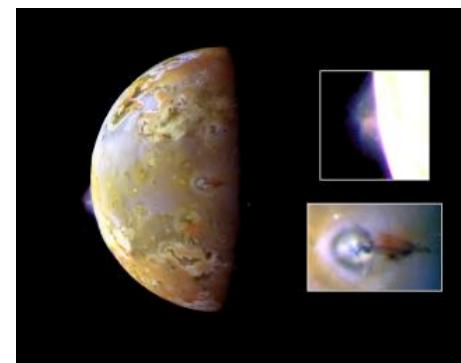
- **Données**
 - surface (imagerie, rayon, spectroscopie)
 - Intérieur (champ de gravité →masse, degré de différentiation; champ magnétique (degré de différentiation))
- **Objets**
 - Cérès ([Dawn](#))
 - Les petits satellites de Saturne ([Cassini](#)) – Japet, Encelade et les autres
 - [Europe](#) ([Galileo](#) – [EJSM](#))
 - Callisto - Titan – Ganymède ([Galileo](#) – [Cassini/Huygens](#) – [EJSM](#))
 - Pluton-Charon et KBOs ([New Horizons](#))
- **Modèles**
 - Densité (composition chimique, porosité)
 - Evolution thermique (conduction – convection [timing])
 - Séparation glace/silicates



Les satellites de Jupiter



Volcanisme dans le
noyau d'Europe ?



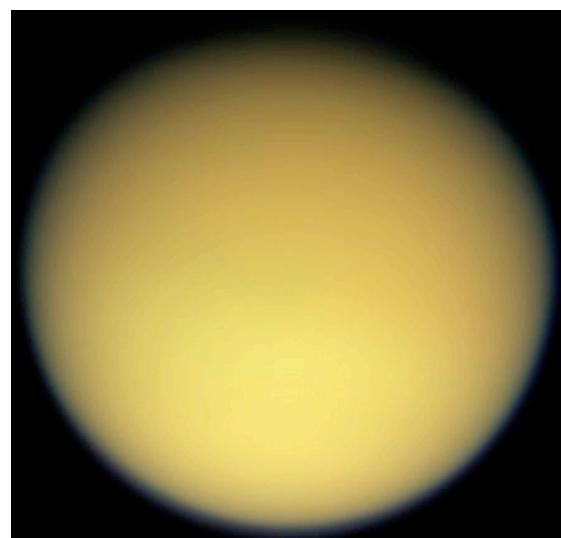


Ganymède – Titan - Callisto

Callisto



Titan



Ganymede



R	2403 km
ρ	$1851 \text{ kg} \cdot \text{m}^{-3}$
MoI	0.358

2575 km
$1881 \text{ kg} \cdot \text{m}^{-3}$
0.340

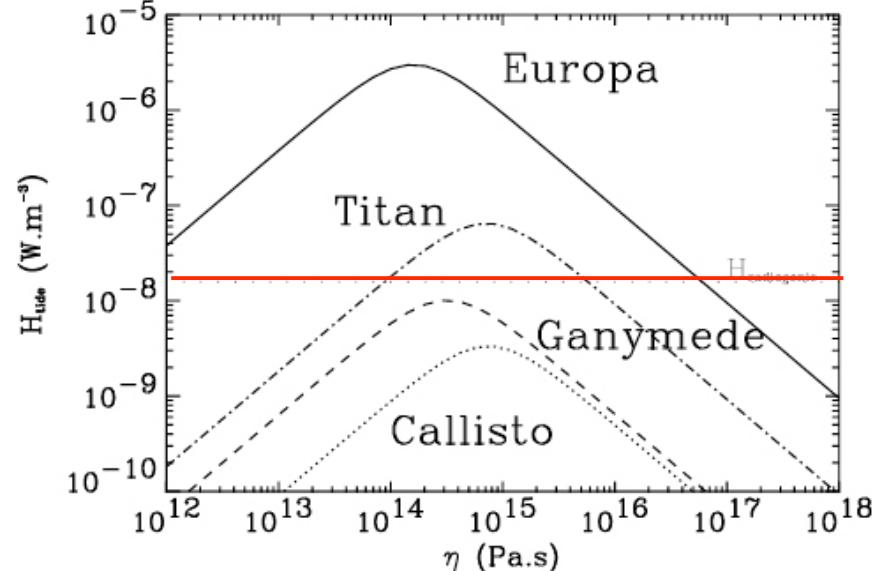
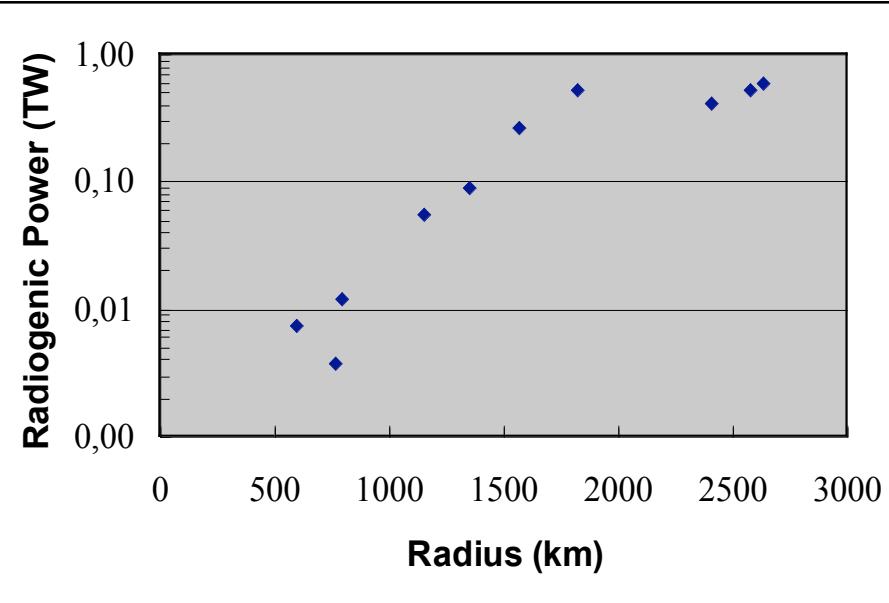
2634 km
$1940 \text{ kg} \cdot \text{m}^{-3}$
0.311



MoI f.=0.4 : homogeneous sphere



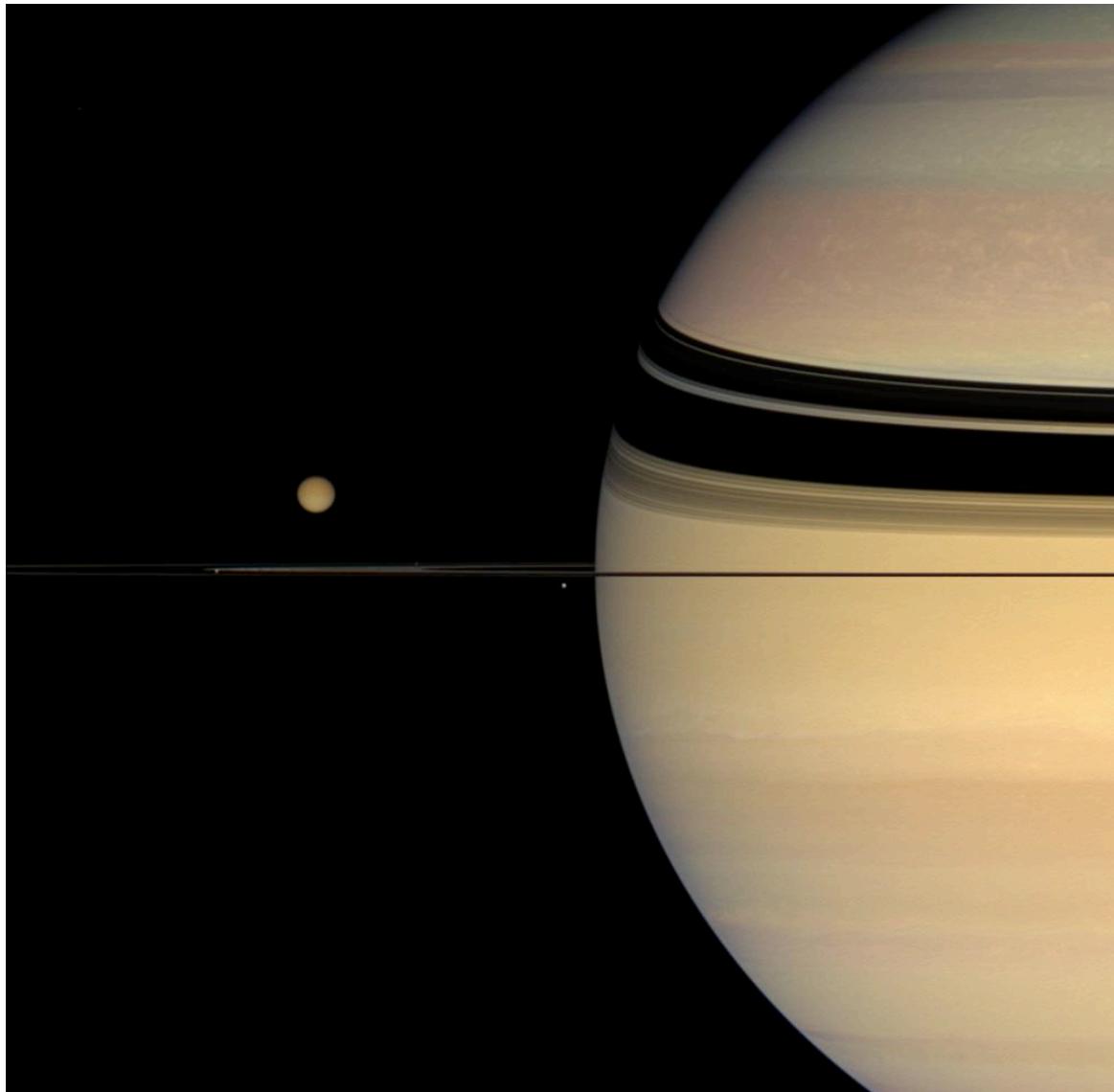
Sources de chaleur



Deux sources de chaleur : Radioactivité et chaleur de marée
Chaleur radioactive 3 fois plus forte il y a 4,5 Ga



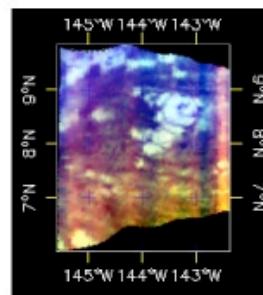
Titan: satellite de Saturne



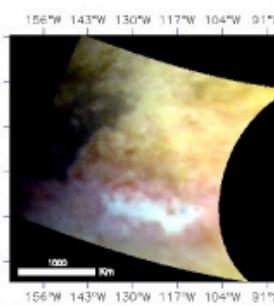


Titan: camera infrarouge

Tortola facula



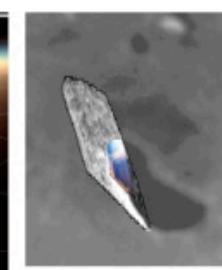
Tui regio



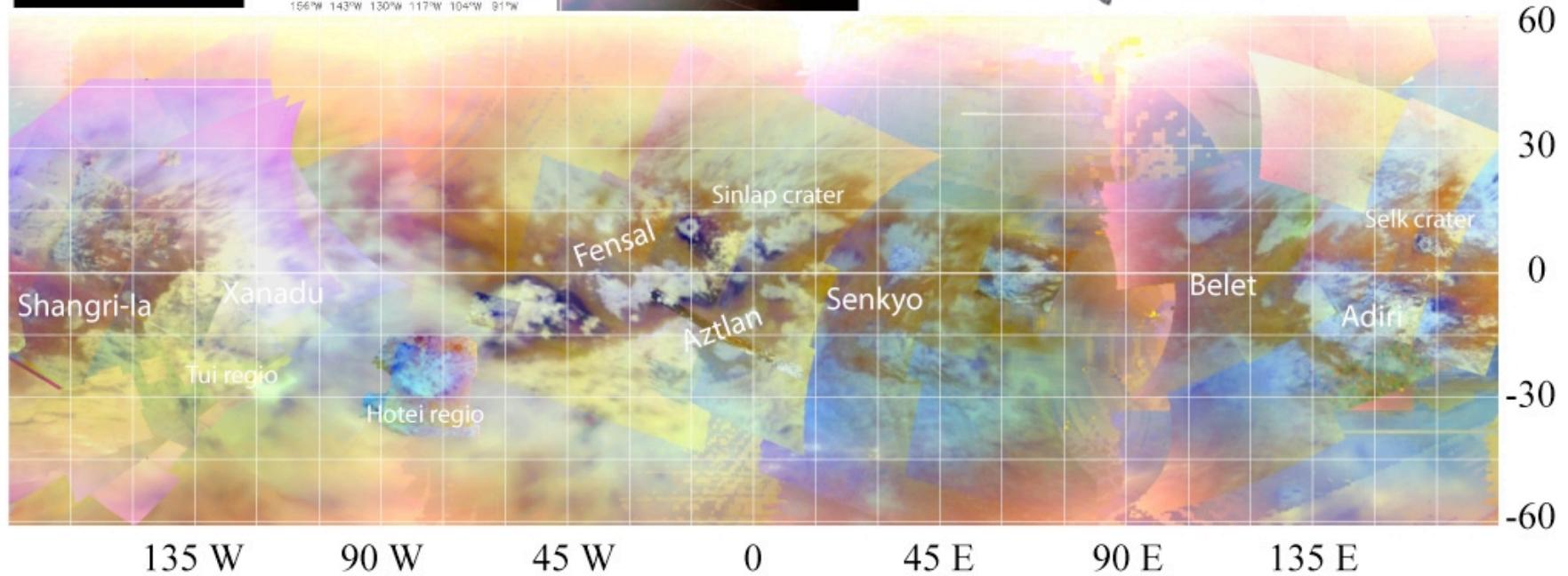
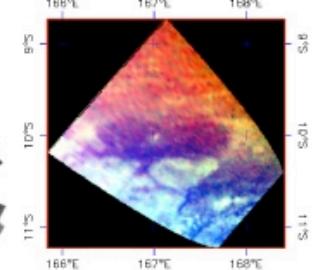
North polar hood



I Ontario lacus

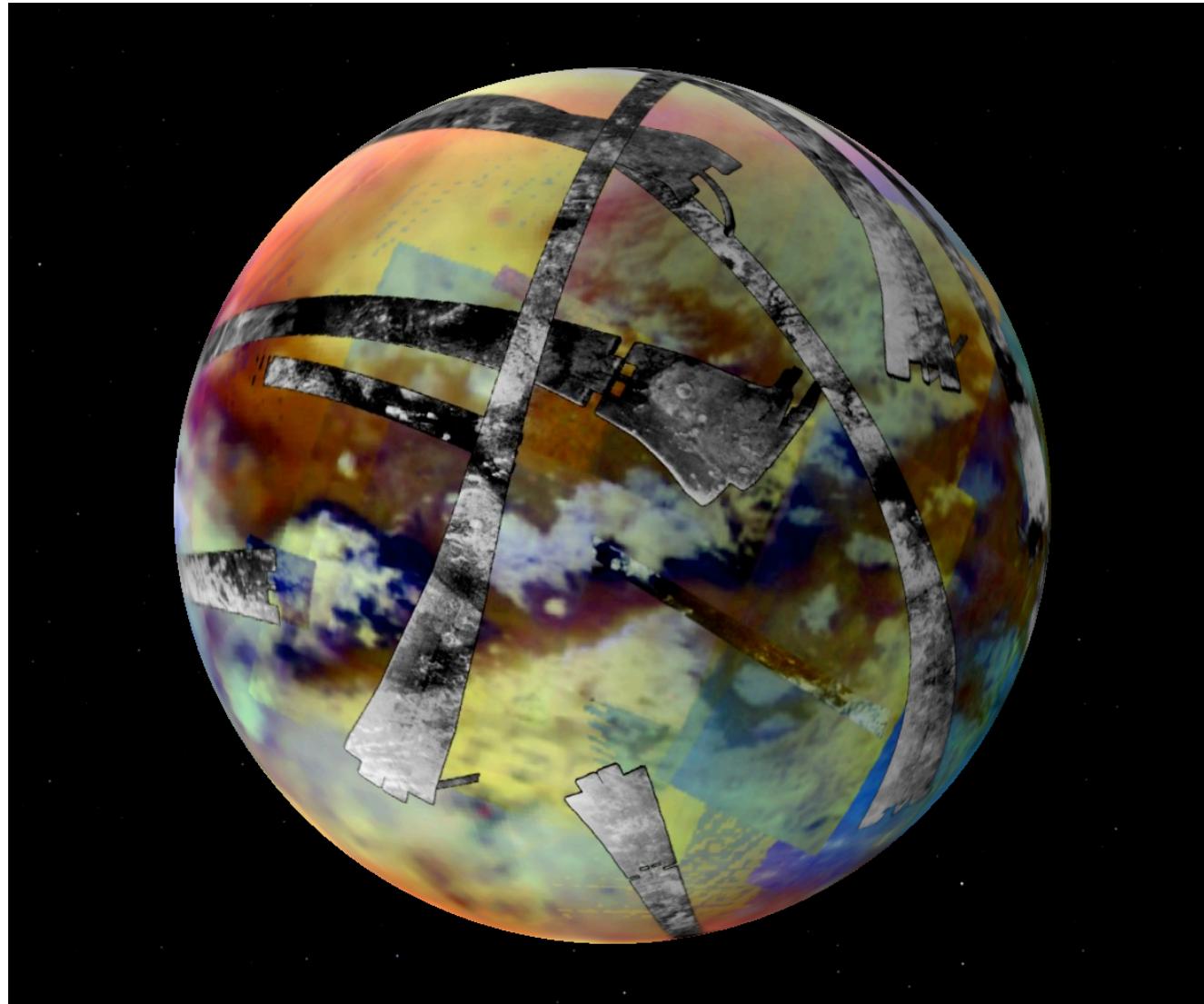


Huygens landing site
DISR VIMS



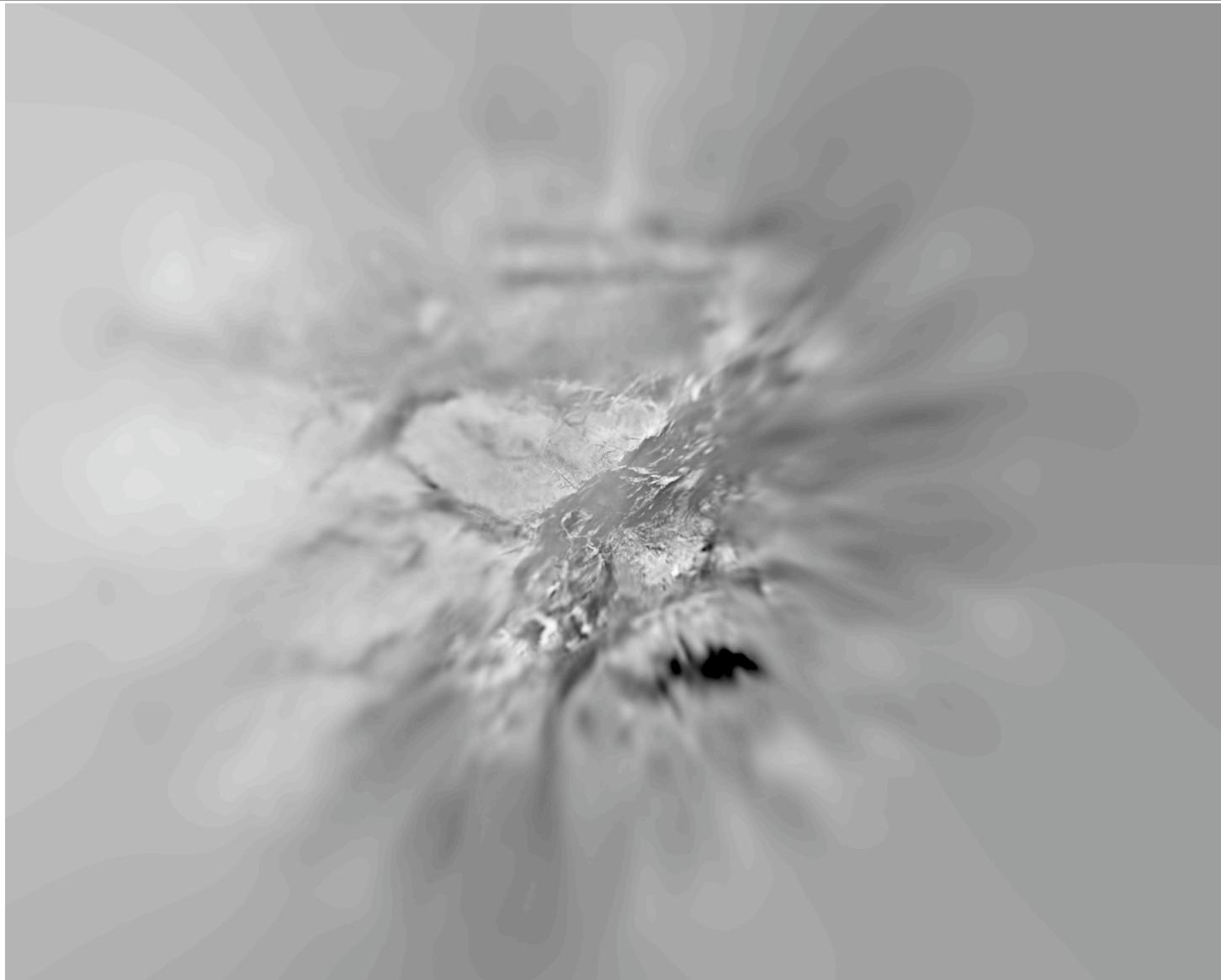


Titan: images radar et infrarouge



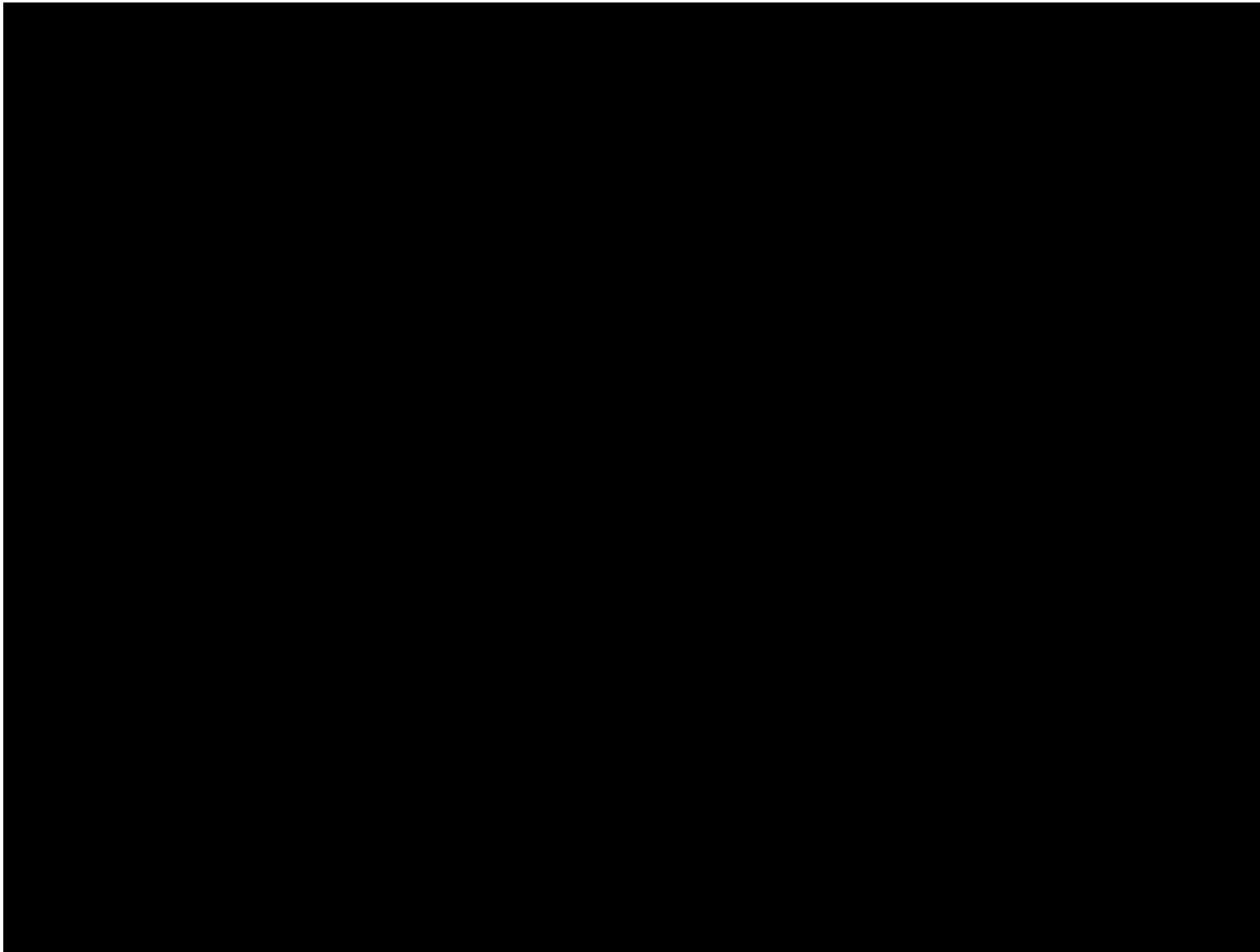


Titan: Site Huygens



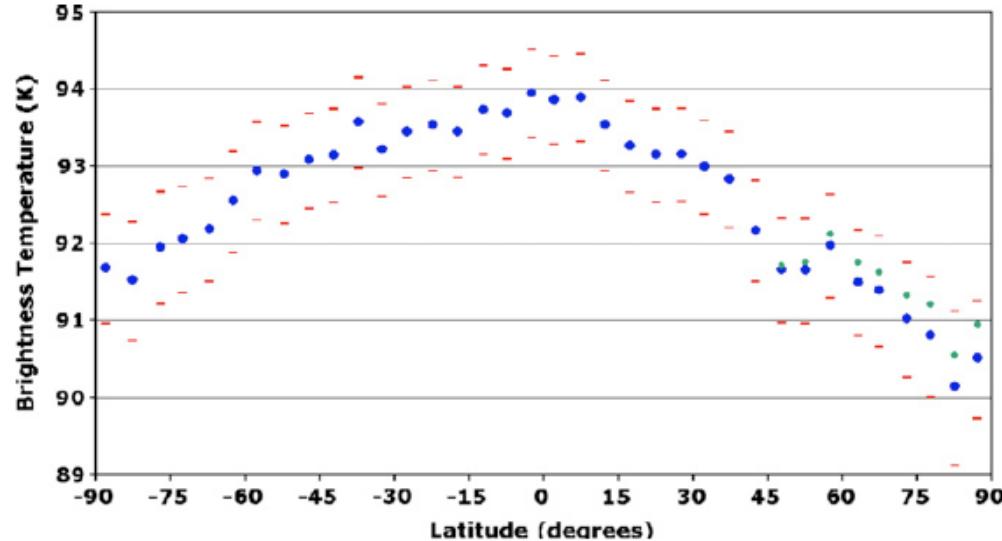


Titan: Site Huygens

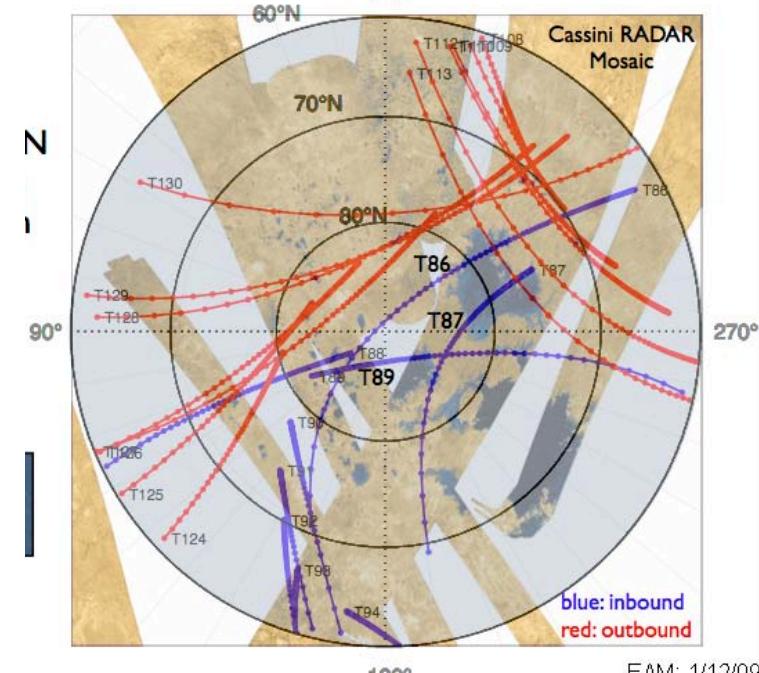
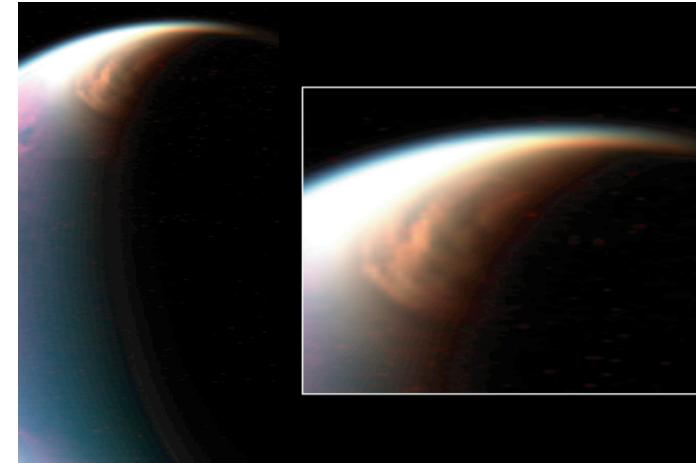




CIRS – surface temperature



Jennings et al; 2009 – CIRS data at $19 \mu\text{m}$.
Inversion de ce profil avec le passage à l'été.
Circulation de nuages d'éthane au dessus du pole Nord.
Lacs principalement au pole Nord (radar)
Mission étendue 2010-2017.

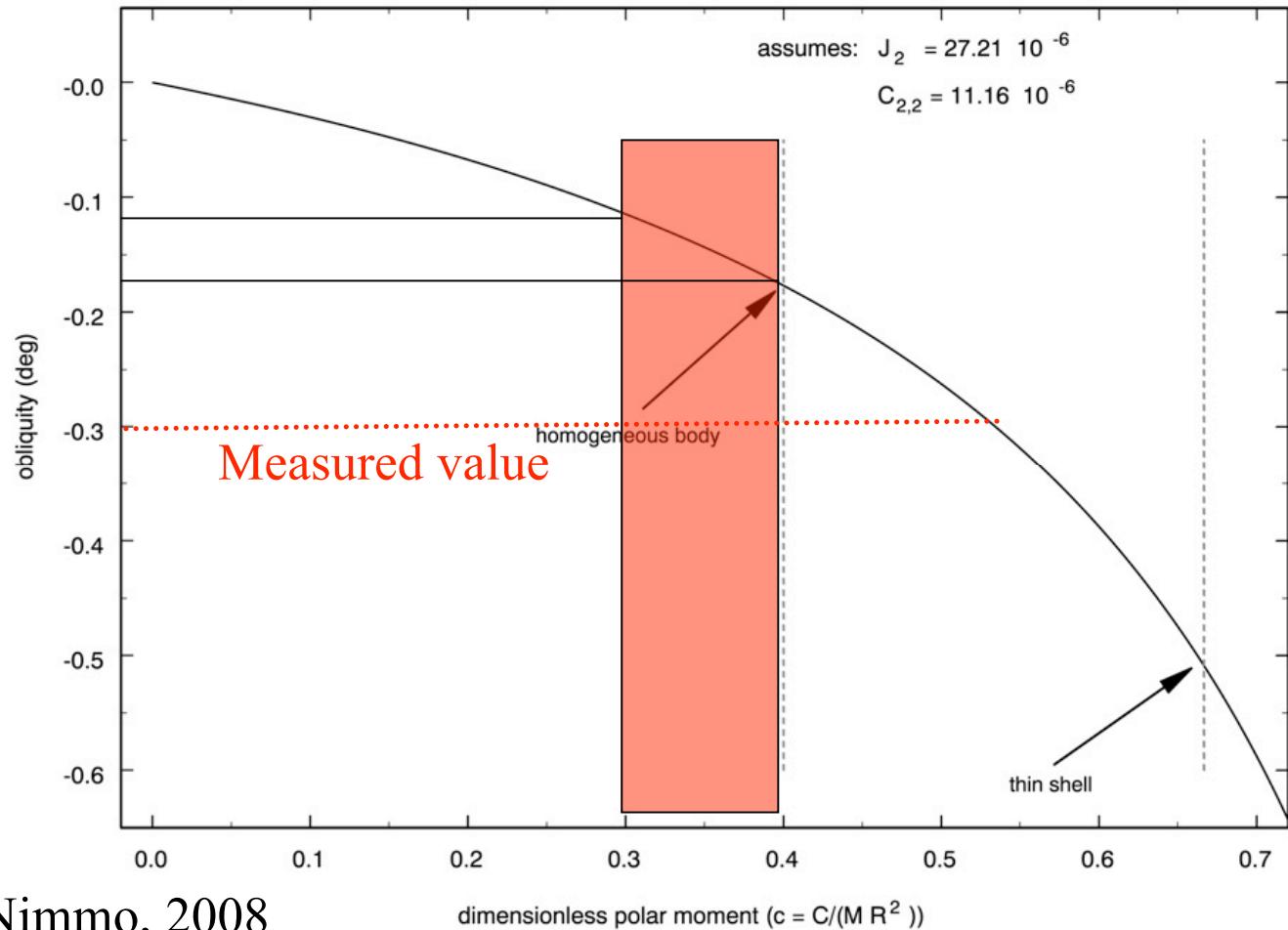




Titan est différencié

- The Cassini state: predictions of obliquity
- Relationships between obliquity and interior structure
- Eccentricity and interior structure
- Librations

$$C/MR^2 = 0.34$$

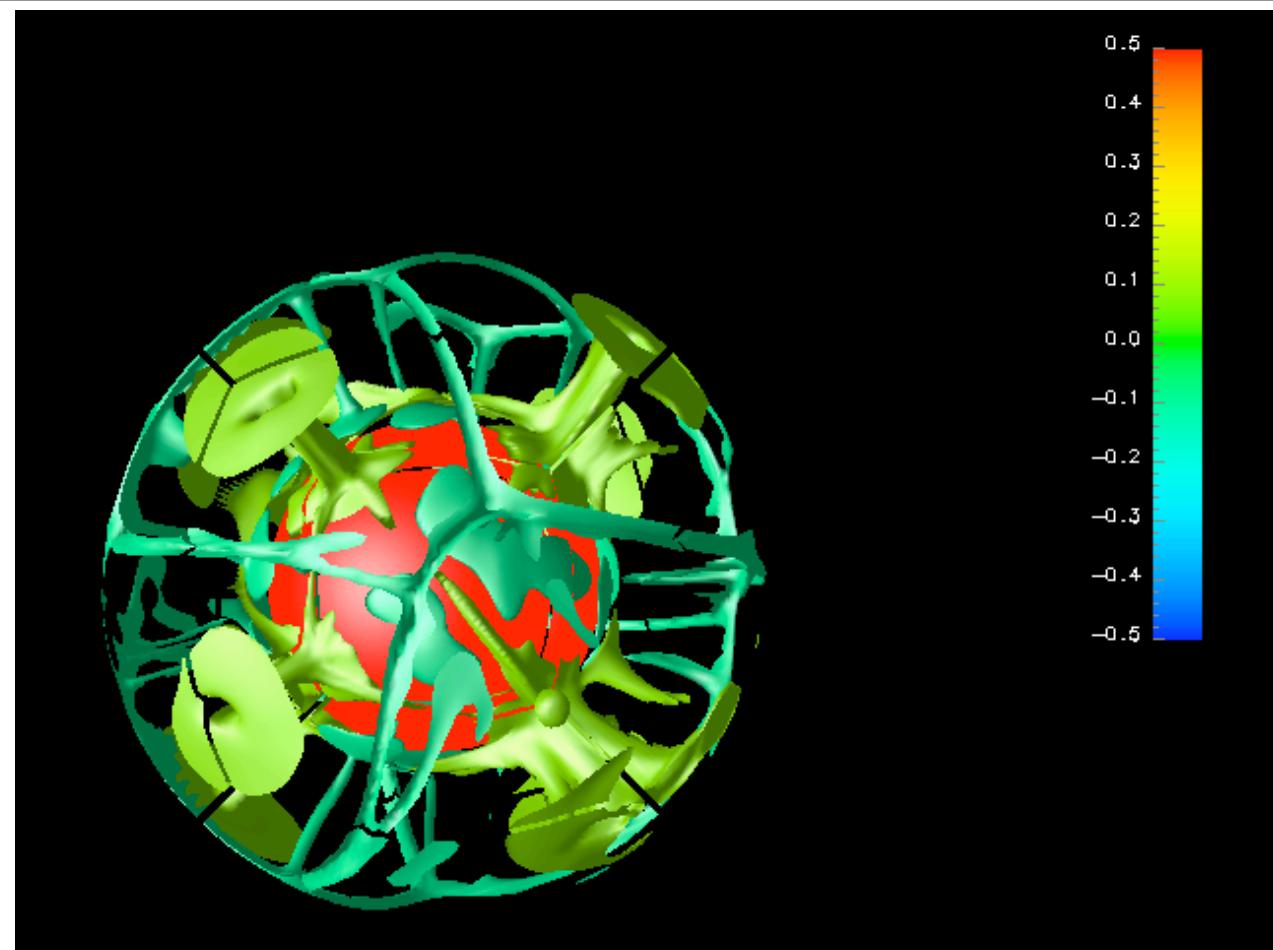


Bills and Nimmo, 2008



Spherical geometry

- Heat flux at the lower interface is higher and can favor hot upwelling plumes
- No internal heating In this case



Oedipus code – Choblet (2005) and Choblet & al (2007)



Temperature and Heat-Flux from the TBL analysis

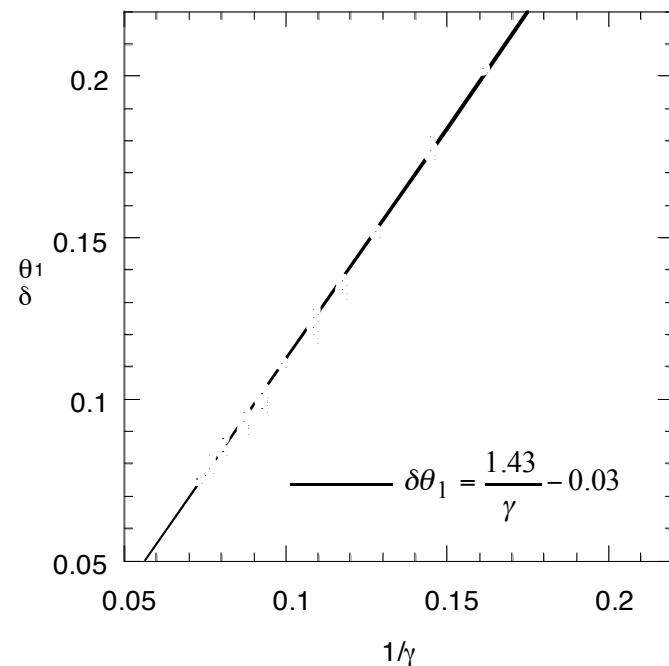
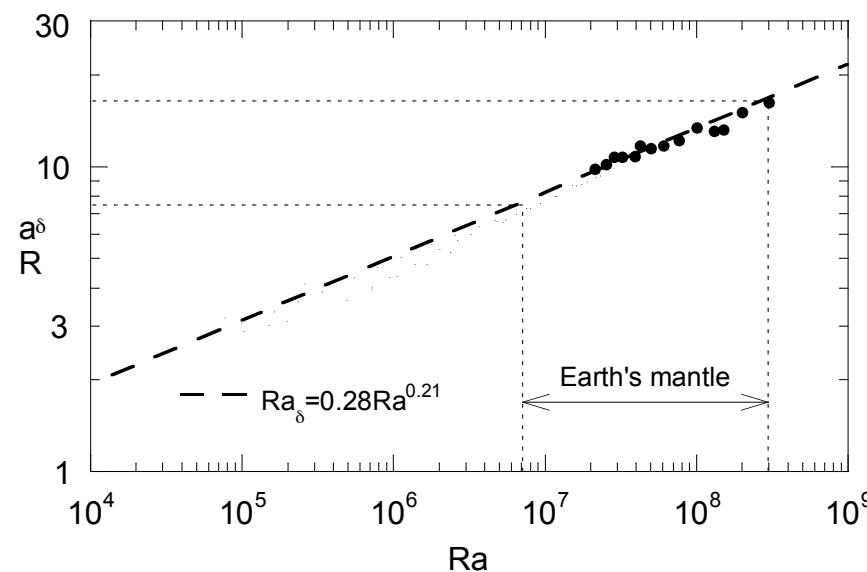
Moresi, L.-N. and Solomatov, V.S., 1995. Numerical investigation of 2D convection with extremely large viscosity variations, *Phys. Fluids*, 7, 2154-2162

Deschamps F., Sotin C., 2000, Inversion of 2D numerical convection experiments for a strongly temperature-dependent viscosity fluid, *Geophys. J. Int.*, 143, 204-218

$$q = k \frac{\Delta T_{TBL}}{\delta_{TBL}} = k \frac{\Delta T}{b} \left(\frac{\Delta T_{TBL}}{\Delta T} \right)^{4/3} \left(\frac{Ra}{Ra_{TBL}} \right)^{1/3}$$

$$\Delta T_\mu = \left| \frac{1}{\partial \ln(\mu) / \partial T} \right|$$

$$\frac{1}{\gamma} = - \frac{1}{\partial \ln(\eta) / \partial T} = \frac{RT^2}{Q}$$





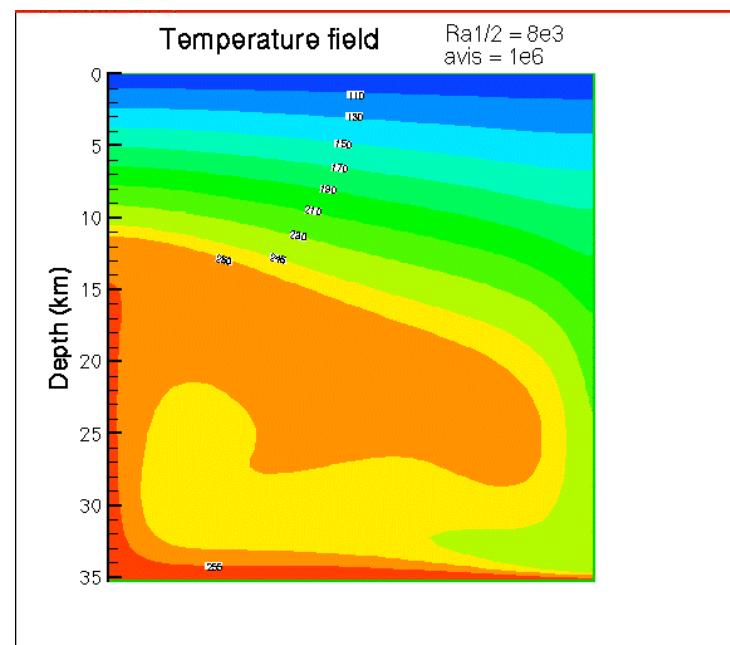
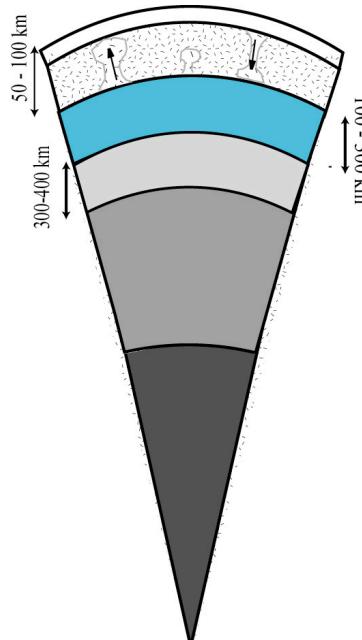
Convection within the outer ice I shell

Temperature profile strongly depends on the viscosity law. Most dramatic effect is the temperature dependence. But other parameters such as grain size and stress dependence are also important

$$Ra = \frac{\alpha \rho g (T_{bot} - T_{top}) D^3}{\kappa \mu T_{mean}}$$

$$\mu = \mu_0 \exp\left(\frac{Q}{R.T}\right)$$

$$\Delta T_{TBL} = 1.43 \Delta T_\mu = 1.43 \frac{RT_{mean}^2}{Q} \quad \Delta T_\mu = \left| \frac{1}{\partial \ln(\mu) / \partial T} \right|$$



$$q = k \frac{\Delta T_{TBL}}{\delta_{TBL}} = k \frac{\Delta T}{b} \left(\frac{\Delta T_{TBL}}{\Delta T} \right)^{4/3} \left(\frac{Ra}{Ra_{TBL}} \right)^{1/3}$$

$$\mu = \mu_{T_{mean}} \exp\left(\gamma \frac{T_{mean} - T}{T_{bot} - T_{top}}\right)$$

$$\frac{R.T_{mean}^2}{Q} = \frac{T_{bot} - T_{top}}{\gamma}$$

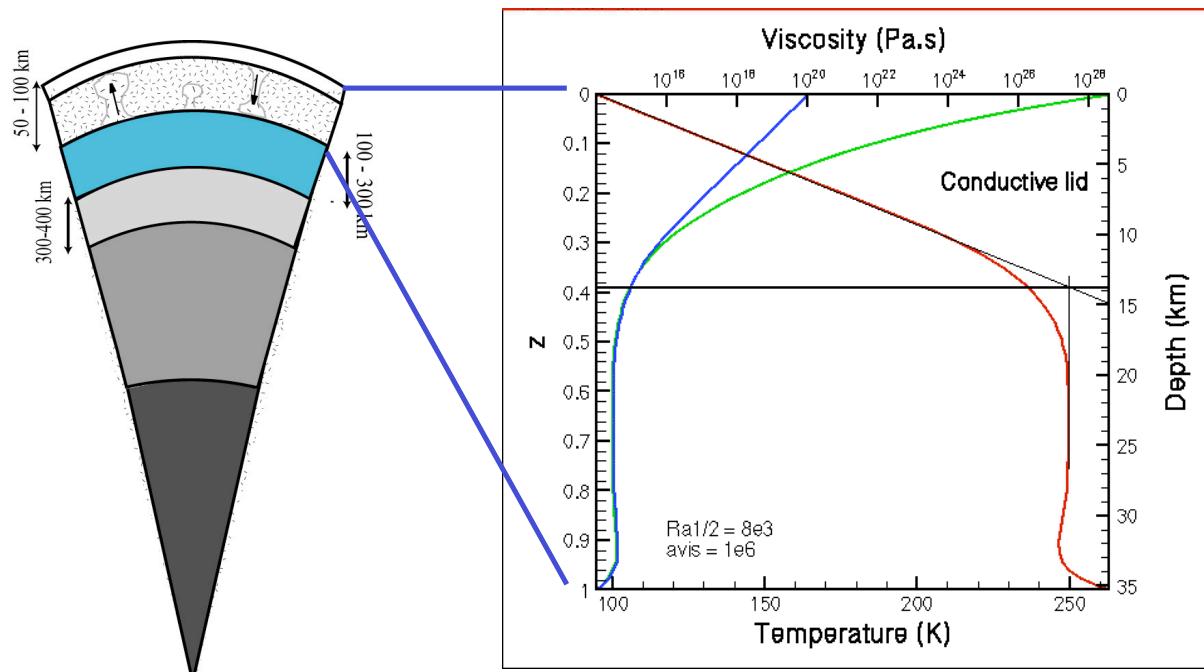


Convection within the outer ice I shell

For numerical reasons, a more simple law is used. But most of the differences occur in the conductive lid where heat is transferred by conduction.

$$Ra = \frac{\alpha \rho g (T_{bot} - T_{top}) D^3}{\kappa \mu_{T_{mean}}} \quad \mu = \mu_{T_{mean}} \exp\left(\gamma \frac{T_{mean} - T}{T_{bot} - T_{top}}\right)$$

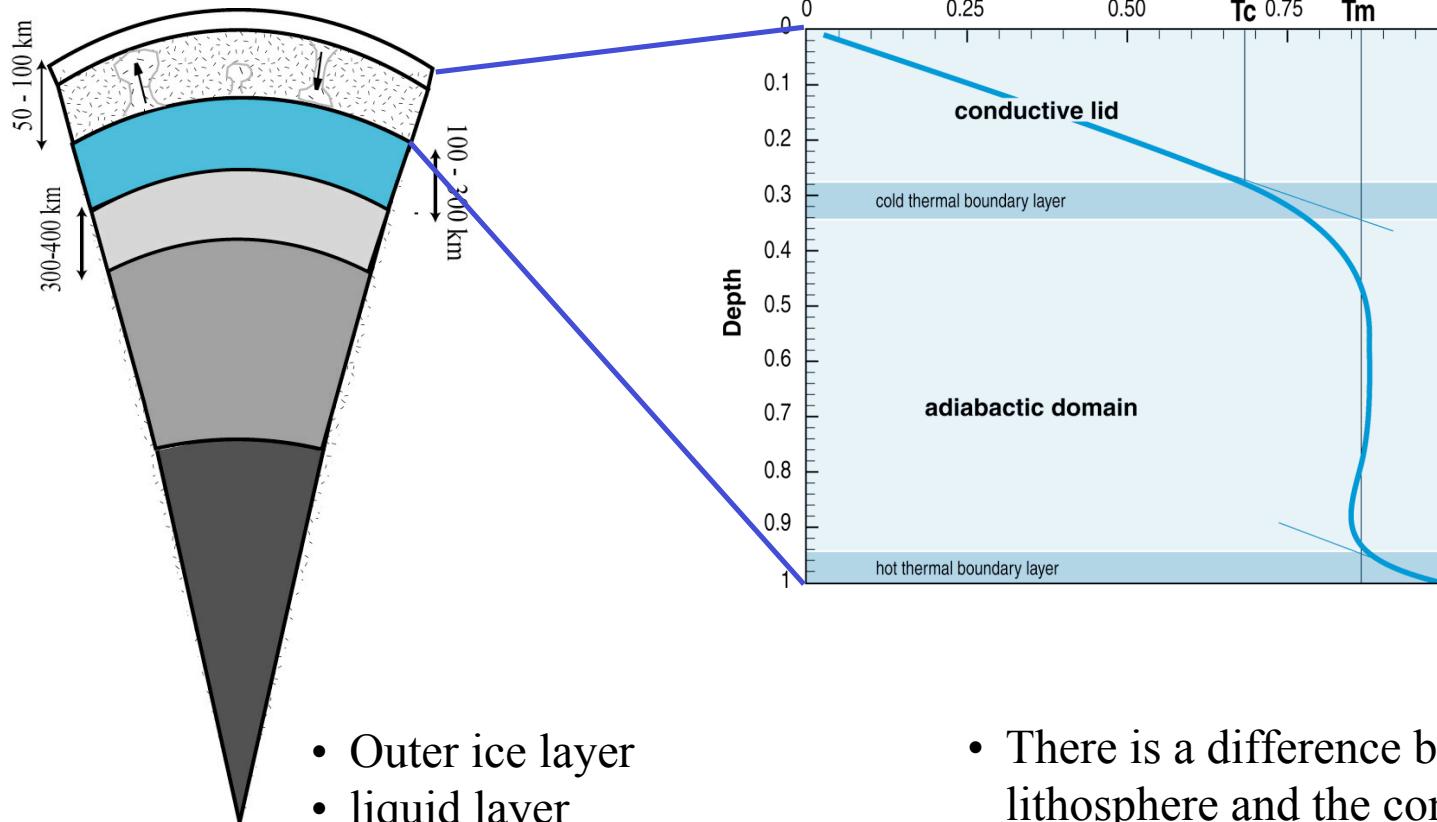
$$\Delta T_{TBL} = 1.43 \Delta T_\mu = 1.43 \frac{RT_{mean}^2}{Q} = 1.43 \frac{(T_{bot} - T_{top})}{\gamma}$$



$$\frac{RT_{mean}^2}{Q} = \frac{T_{bot} - T_{top}}{\gamma}$$



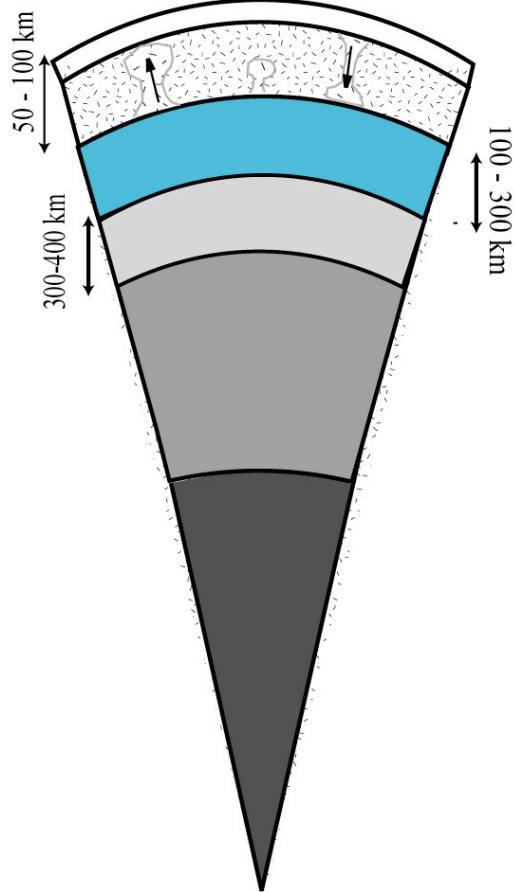
Convection in the ice crust



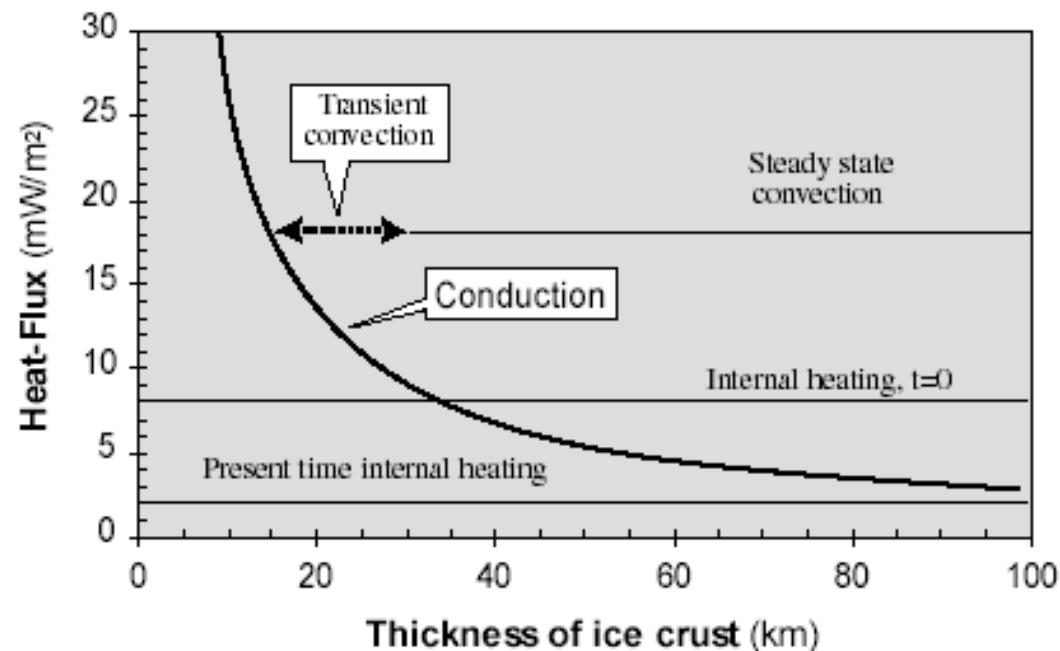
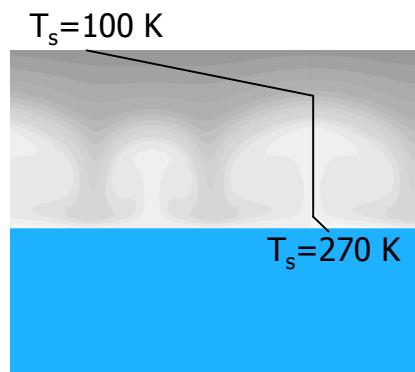
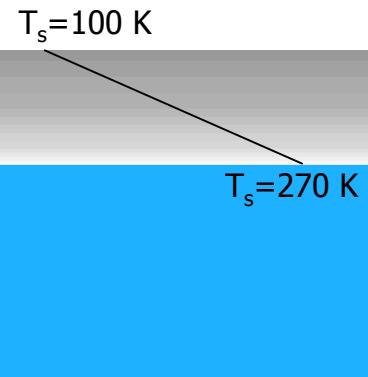
- There is a difference between the lithosphere and the conductive lid
- The temperature difference between the ocean and the convective layer is small (10 K)



Thermal evolution



conductive or convective ?

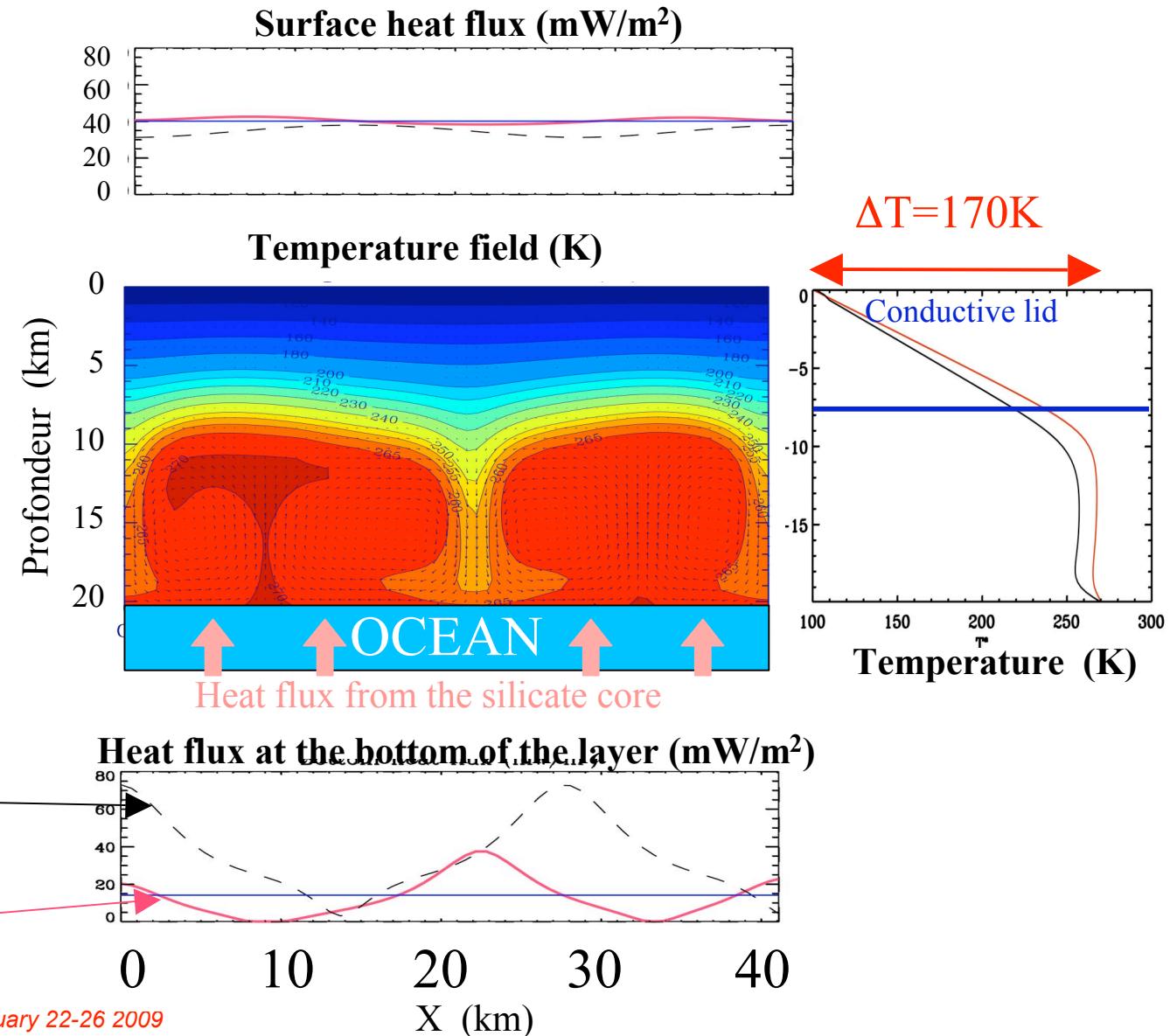




One example of numerical experiment

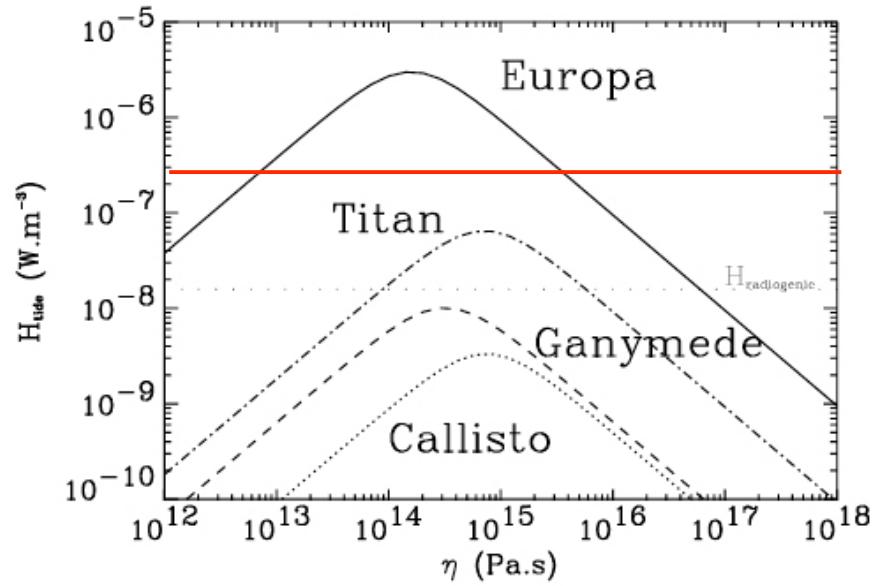
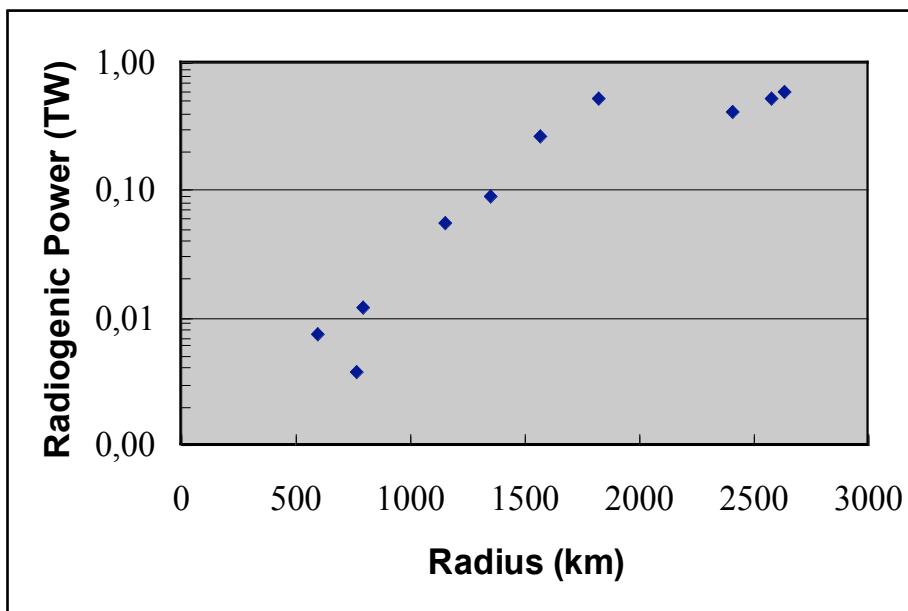
Europa:
 $b = 20 \text{ km}$
 $\eta_b = \eta_{\max} = 1.5 \times 10^{14} \text{ Pa.s}$
 $\text{Ra} = 1.6 \times 10^6$
 $H_{\max} = 2.7 \times 10^{-6} \text{ W.m}^{-3}$

Heat flux is constant out of the conductive lid.





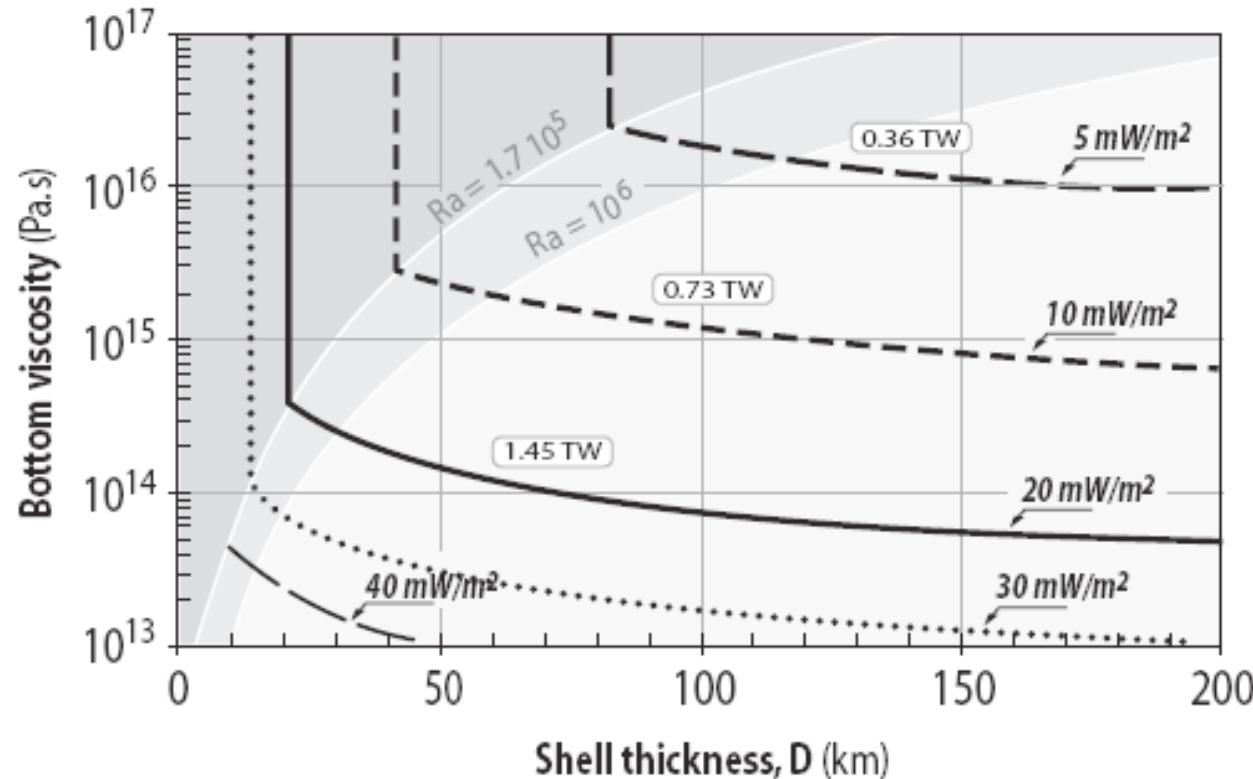
Heat sources



Cf presentation by Tobie.



Stationary convection



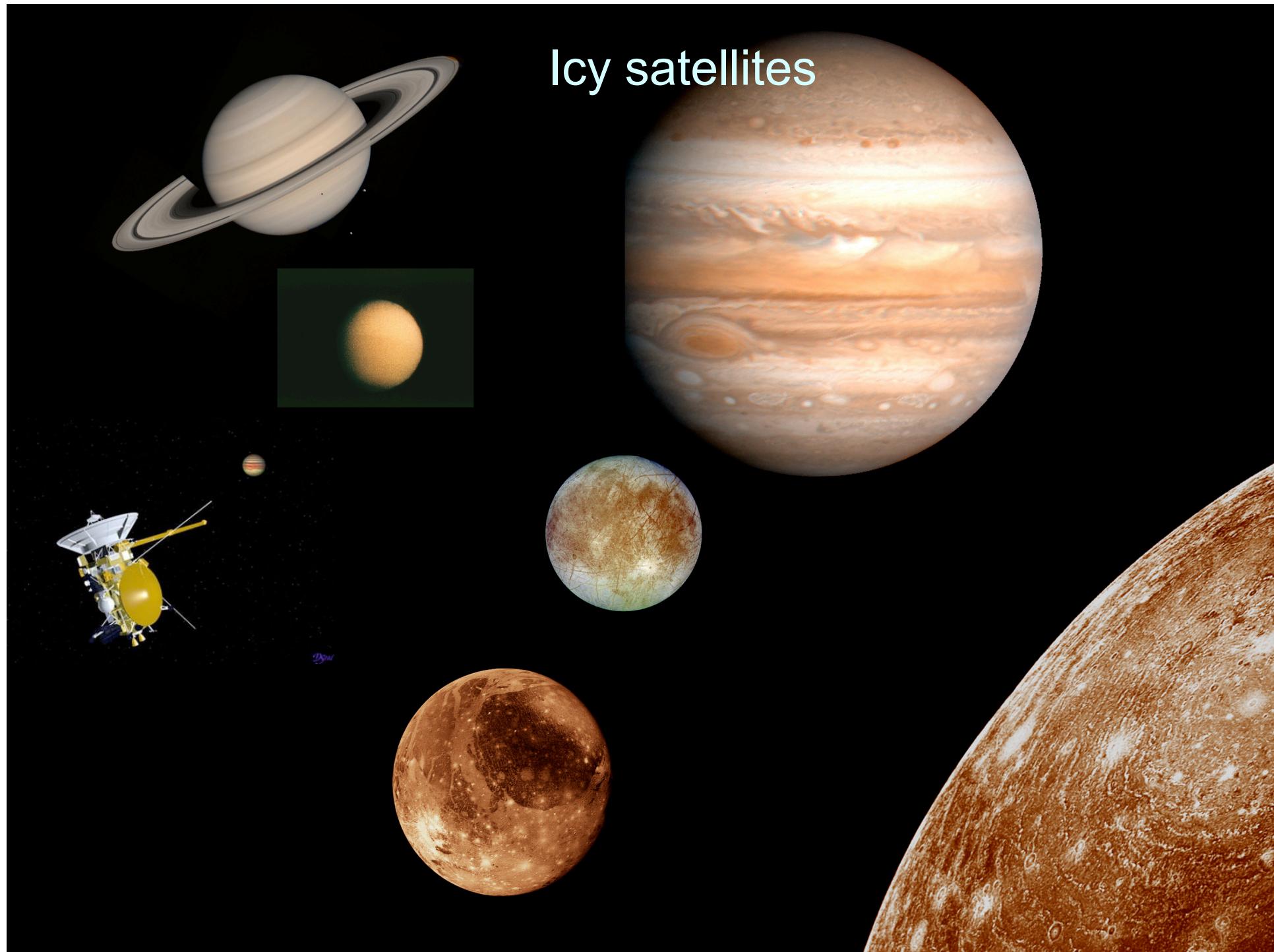
- Heat transferred by conduction depends only on the thickness of the crust.
- Heat transferred by convection depends mostly on the viscosity.
- If convective heat transferred by convection is larger than internal heat production, then the satellite cools down.
- A liquid layer can be maintained over geological time scales if “convective heat transfer” equals internal heat

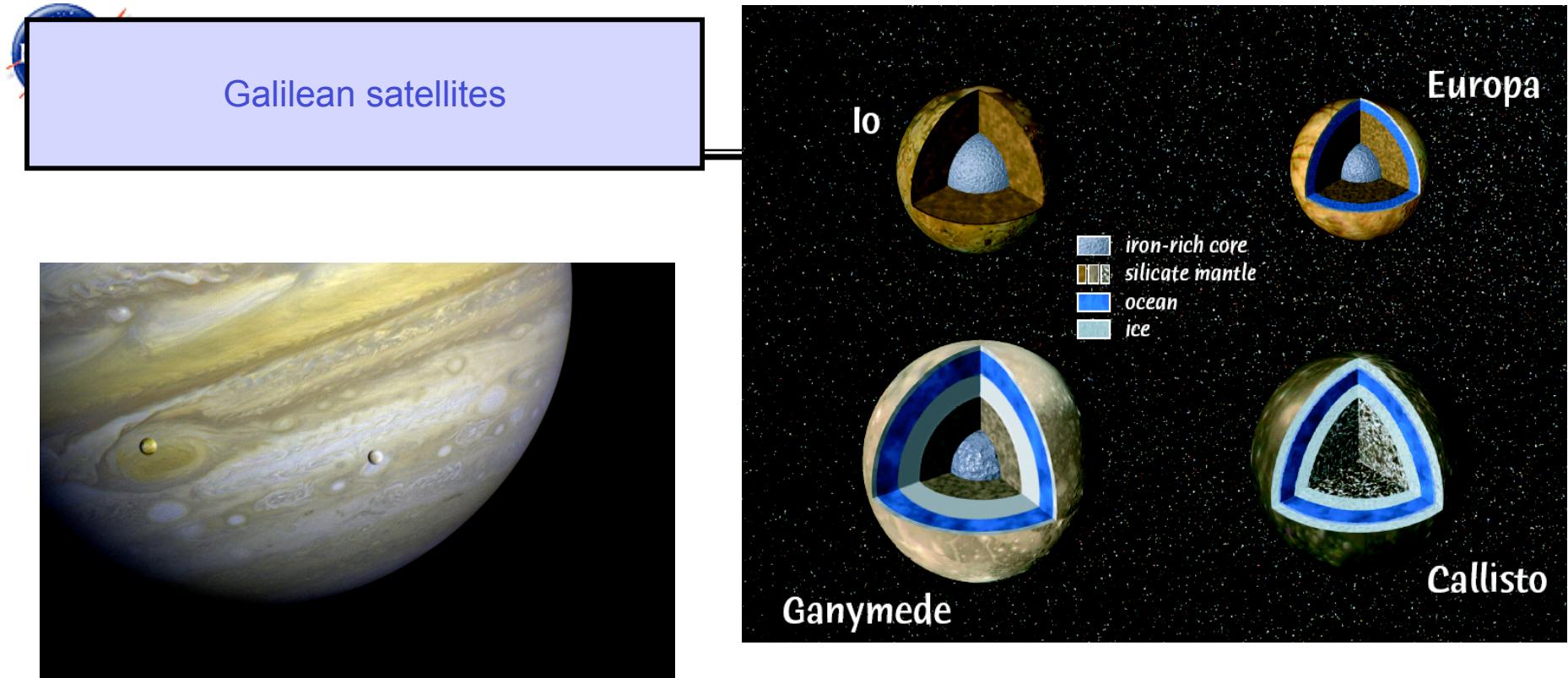


Conclusions

- Convection is a process that can transport material from the interior to the subsurface.
- On Earth, convection leads to plate tectonics, a process that breaks the lithosphere and melt produced at depth can migrate to the surface.
- Convection is possible in the ice layer with hot plumes. Convection does not lead to plate tectonics (Europa ?)
- A liquid layer can be maintained over geological time scales if “convective heat transfer” equals internal heat
- Viscosity profile can be used to calculate amount of dissipation – They must agree with the eccentricity and other observables.
- Convection can occur even in small satellites and can prevent differentiation in the case of pure water ice.
- In the case of Iapetus, a complex viscosity (different viscosities for different forcing periods) is necessary to explain despinning.

Icy satellites

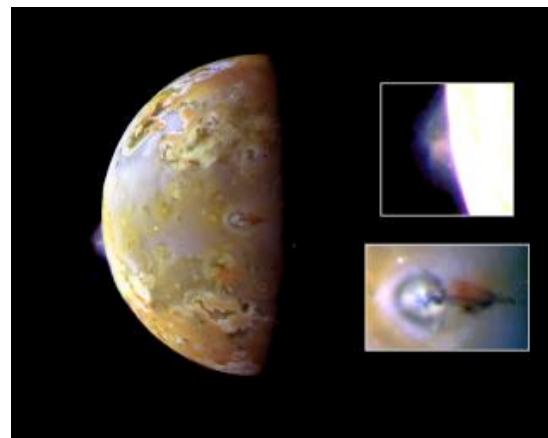




volcanism on Io

$$2 < \varphi_{\text{surf}} < 12 \text{ W/m}^2$$

If silicate volcanism exists within icy satellites, there may be conditions similar to those existing at mid-ocean ridges ...only for Europa (HP ices for the two others)





Orbital and physical data

$$C = \int_M x^2 dm = \iiint r^4 \rho(r, \theta, \psi) \sin^3(\theta) dr d\theta d\psi = \frac{8\pi}{15} \left(\rho_M \left(R^5 - R_c^5 \right) + \rho_c R_c^5 \right)$$



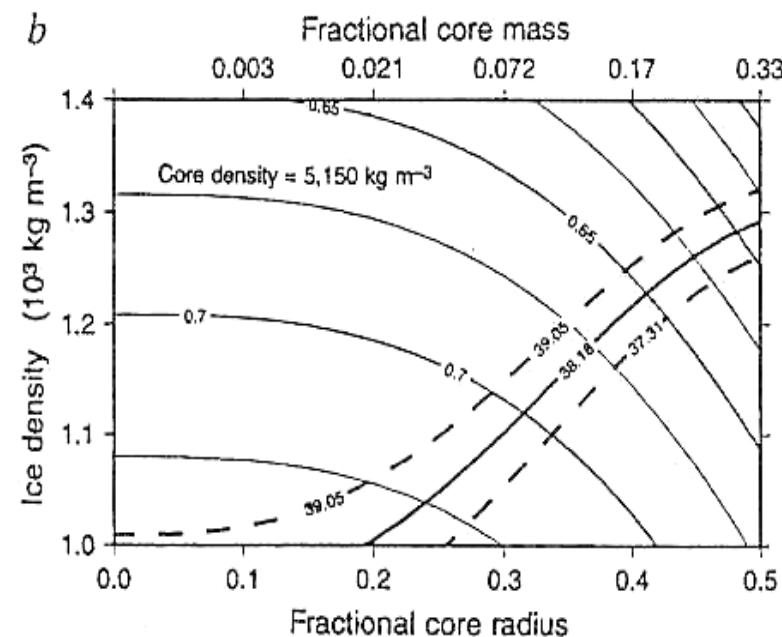
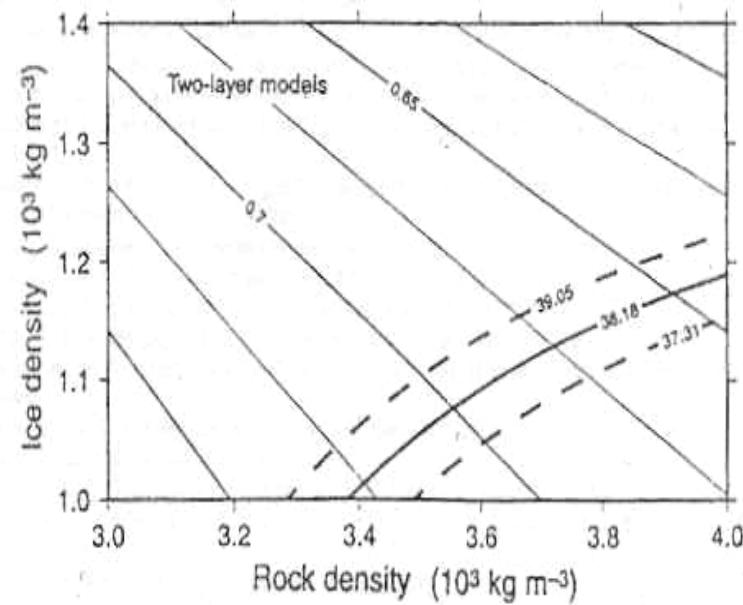
	ρ (kg/m ³)	Radius (km)	C/MR ²	e	Prot (days)
IO	3528	1822	0,377	0,004	1,77
EUROPA	2970	1569	0,347	0,010	3,55
GANYMED	1940	2634	0,311	0,0015	7,15
CALLISTO	1851	2403	0,358	0,007	16,70
TITAN	1881	2575	?	0,029	15,95

$$M = \int_M dm = \frac{4\pi}{3} \left(\rho_M \left(R^3 - R_c^3 \right) + \rho_c R_c^3 \right) \quad C/MR^2 = 2/5 \text{ if the satellite is not differentiated}$$



Case of Ganymede (Schubert et al., 1999)

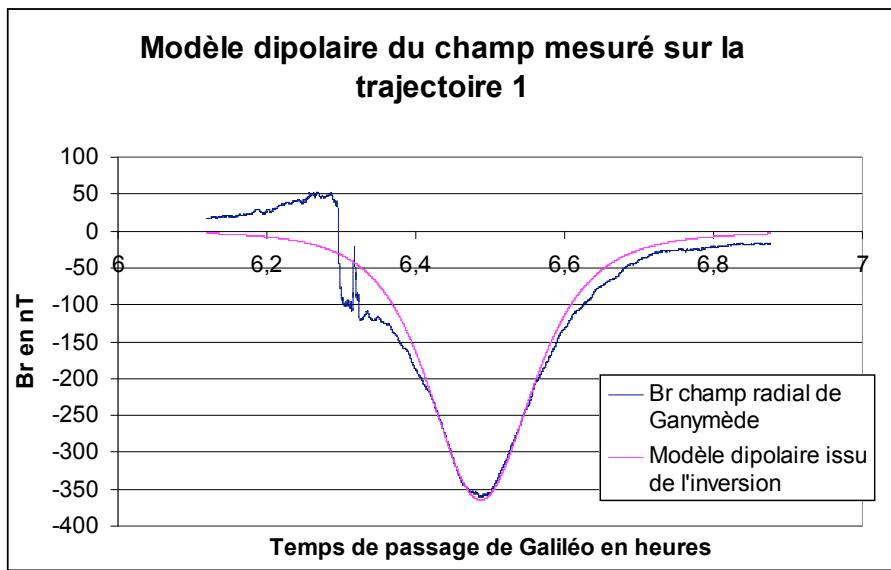
$$C = \frac{8\pi}{15} \left(\tilde{n}_M \left(R^5 - R_S^5 \right) + \rho_S \left(R_S^5 - R_c^5 \right) + \rho_c R_c^5 \right)$$



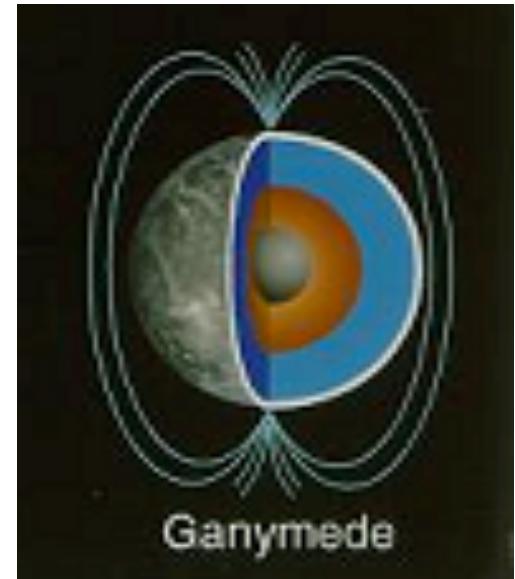
$$M = \frac{4\pi}{3} \left(\rho_M \left(R^3 - R_S^3 \right) + \rho_S \left(R_S^3 - R_c^3 \right) + \rho_c R_c^3 \right)$$



Magnetic data : observations



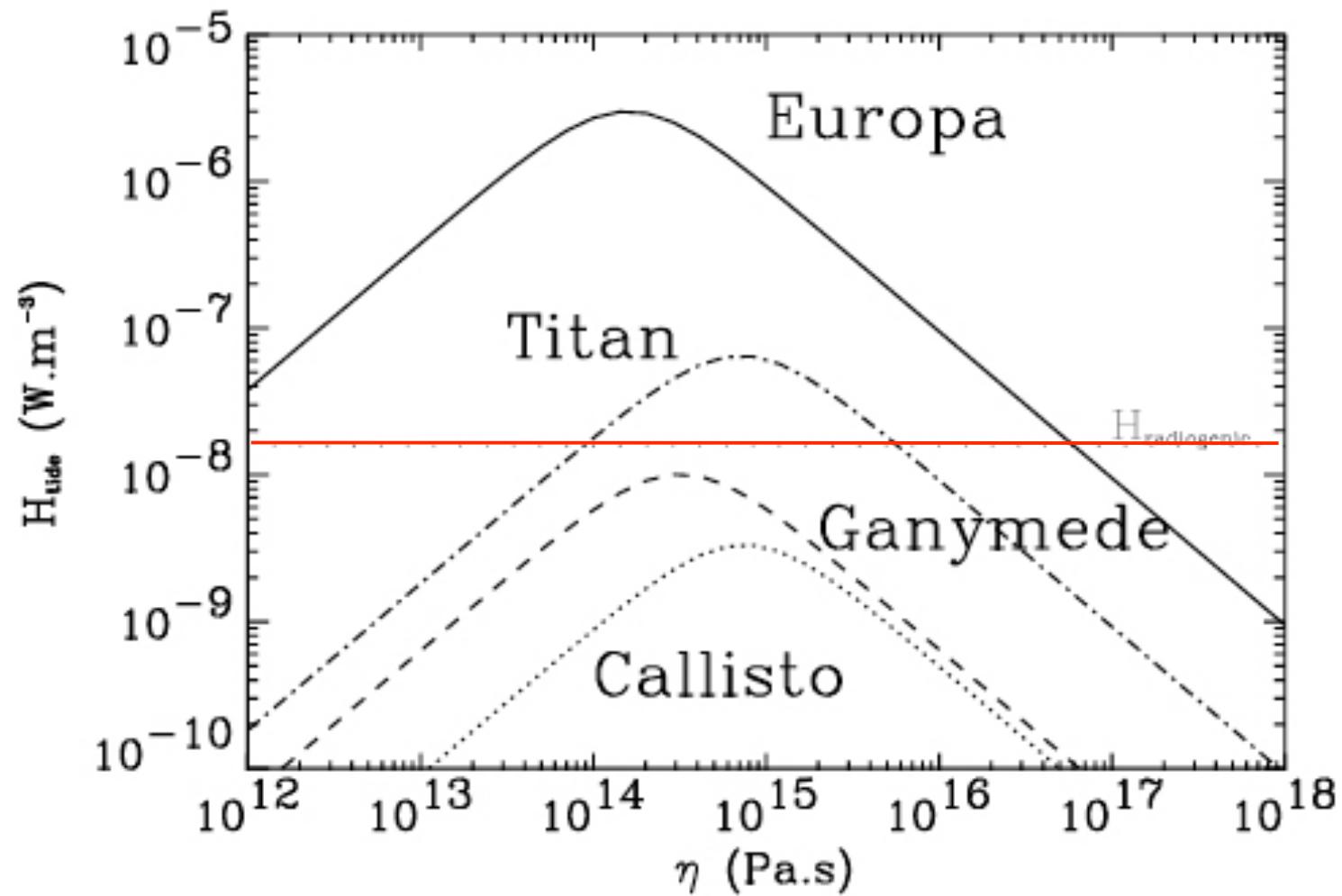
Major surprise of the Galileo mission was the discovery of an intrinsic magnetic field within Ganymede (Kivelson, 1996)



Trajectoire	Date	Altitude (km)	Latitude /Ganymede	Longitude /Ganymede
G1	27/06/1996	838	30	247
G2	06/09/1996	264	79	236
G7	05/04/1997	3105	56	270
G8	07/05/1997	1606	28	85
G28	20/05/2000	900	-13	269



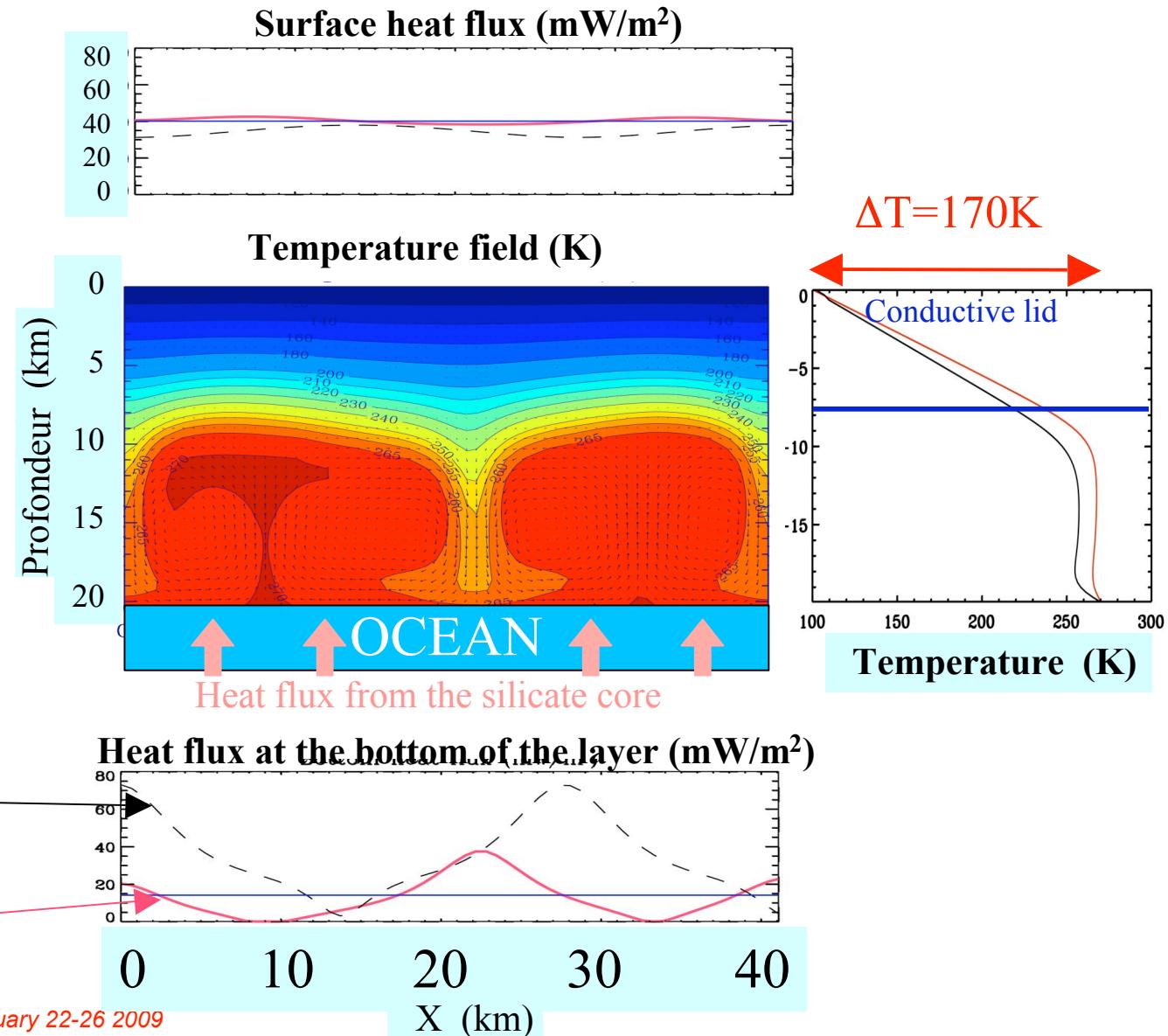
Dissipation in the ice I layer





One example of numerical experiment

Europa:
 $b = 20 \text{ km}$
 $\eta_b = \eta_{\max} = 1.5 \times 10^{14} \text{ Pa.s}$
 $\text{Ra} = 1.6 \times 10^6$
 $H_{\max} = 2.7 \times 10^{-6} \text{ W.m}^{-3}$





Europe-Titan: similarities and differences

